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Predictive Corrosion Models to Mitigate Environmental Hazards on Ground Assets

by Daniel Pope, James A. Ellor, John P. Repp,
C. Thomas Savell, Thomas A. Considine, and Lindsey M. Blohm

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14. ABSTRACT
Coating degradation on U.S. Army ground systems incurs significant maintenance cost. The objective of this proposed work is to develop a predictive Bayesian model for coating degradation and subsequent substrate corrosion on Army ground assets. With a better understanding of the root causes, steps can be taken to reduce corrosion impacts on Army materiel. In this effort, a model was created by incorporating significant analysis and learning from field surveys of over 15,000 assets and 250,000 components, coatings performance following standardized testing, and observations of coating conditions on fielded items. Model outputs will provide basic support to a Commodity Manager to determine optimal repaint intervals and minimize expenditures as well as assist in developing new products/processes beneficial to coating performance and yield increased life expectancy of an asset's protective coating systems.

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Executive Summary

Overview

Corrosion and coating degradation results in a significant maintenance burden on U.S. Army ground systems. This maintenance burden undermines operational readiness. Corrosion maintenance using corrosion inhibiting compounds (CICs) and coating materials can additionally create an environmental impact depending on the materials used. This can expose technicians and the environment to potential hazards (e.g., hexavalent chromium, volatile organic compounds, hazardous air pollutants) during repair. The present effort examined the ability to develop a model relating the use of specific coating materials and processes to the coating system longevity on ground assets. Development of such a model would aid future material development by focusing efforts on key contributors to coating performance.

For ground systems, the Army maintains three general approaches to corrosion maintenance: preventative maintenance, spot repairs, and full repainting. Minor corrosion is controlled via the periodic application of CICs as preventative maintenance. When coatings begin to break down or are no longer providing complete protection, maintenance may incorporate a combination of CIC application and spot painting. Extensive corrosion and coating failure are addressed via complete painting removal and repainting of the asset.

In support of the Army's Corrosion Prevention and Control program, the Army invests in testing protective coating systems. Many of the materials evaluated are the result of emerging environmental and regulatory concerns. The Army also invests in extensive surveys of ground fleet assets to identify corrosion-prone equipment, systemic problems, and possible solutions.

Objectives

Key research objectives included the following:

- Identify key factors/contributors to coating breakdown on the Chemical Agent Resistant Coating (CARC)[1] system on ground assets.
- Map coating application parameters/variations that have the greatest impact on coating failure and subsequent corrosion of steel components.
- Use research and field datasets supplemented by additional testing to develop a predictive model for corrosion degradation on military assets painted with the CARC system.

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[1] MIL-DTL-53072. Chemical Agent Resistant Coating (CARC) System Application Procedures and Quality Control Inspection. EverySpec; 2003 June 6.

Technology Approach

The present modeling program aimed to leverage Army investments by combining a series of performance data in a Bayesian model, based on U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) testing of various CARC systems and data gathered from field inspections of Army ground assets. ARL data concerning the performance of CARC systems include common system variants applied to ground systems and evaluation of new pretreatment materials. The laboratory data describe the performance of coatings and materials under controlled and monitored conditions. The field inspection data from U.S. Army Tank-Automotive and Armaments Command (TACOM)-sponsored ground vehicle surveys comprises information on more than 20,000 assets with detailed corrosion data and photographs on more than 300,000-part assemblies. Coating loss and corrosion on actual assets represent the results of uncontrolled conditions experienced in-service. Establishing the relationship between asset condition and "laboratory-expected" coating performance includes the following additional factors:

- The actual exposure environment.
    - The corrosivity of equipment stationed in locations with higher times of wetness (TOW) and proximity to salt water are expected to be worse than equipment located in an arid environment.
    - TOW was recorded in hours and categorized into high, medium, and low. Proximity to saltwater effects were categorized as yes or no.
- The use of the equipment.
    - Assets used more frequently than others have a larger strain on these corrosion protection measures due to impact and abrasion from road debris, cargo carrying, Soldiers entering/exiting the vehicle, among others.
    - Furthermore, in the operation of equipment, specific components can be subjected to more physical damage, which exacerbates corrosion tendencies.
- Part complexity and quality of paint application.
    - Army equipment is fabricated from multiple sub-parts, each with its own physical complexity.
    - It is difficult to achieve a high-quality paint system on complex, bolted, or faying surfaces compared with flat surfaces, and flat surfaces are more representative of a "laboratory test panel."

Linking the laboratory results and the field observations was a key challenge. This effort was complicated because the laboratory data were gathered via reference to standard American Society for Testing and Materials or military specification procedures. Field survey data were based on Stages of Corrosion (SoC) ratings (Figure ES-1) as outlined in TB 43-0213.[2] Data concerning asset conditions is a basis for recommended remedial preservation action. The data obtained from laboratory exposures are inspected with more detailed rating systems than the stages given in TB 43-0213.

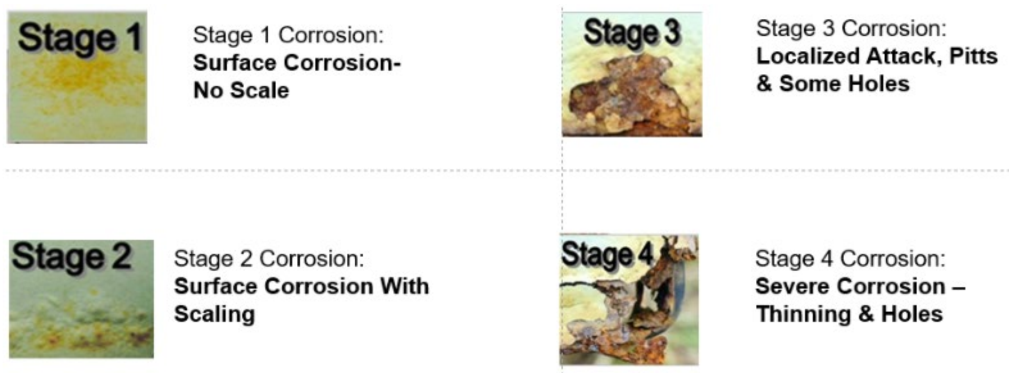

Figure ES-1. SoC ratings.

The ARL data consists of two primary observations: through-film corrosion data and corrosion creep originating from an intentional defect, traditionally referred to as an X-scribe. Although data are available for both accelerated corrosion testing and natural marine exposure (Cape Canaveral Space Force Station; Cape Canaveral, Florida), the present program focused on the natural exposure data, because this more closely represents corrosive damage that might be observed over time on fielded assets. Panels are exposed normally for up to 48 months (2 years).

These laboratory data were gathered on multiple test panels with different CARC systems. The test panels were either abrasive blasted or mill finished prior to chemical pretreatment and coating system application. Chemical pretreatments included common zinc phosphate coatings with sealer, zinc-rich primer, and wash primer or proprietary organic and inorganic pretreatments. From the through-film corrosion data, two parameters were extracted: incubation time and a time rate of ongoing film deterioration. The incubation time was defined as the time of exposure at which the initial film defects were recorded. Based on the number of panels tested and the observations, these data were treated as a Weibull distribution of initial failures or an average value of the reported time to failure. (Limited datasets or censored data limited the application of Weibull statistics to each dataset.) The ongoing deterioration of the coatings after the specific incubation time provided a projection for the growth of the through-film corrosion. The model assumed these

[2] TB 43-0213. Corrosion prevention and control for army ground equipment. Army Tank-Automotive and Armaments Command (US); 1990 Dec 4.

two factors to be independent. Based on a review of the datasets and the governing ranking system, a specific SoC ranking was assigned to specific observations.

The creepage data were converted from a numerical ranking to the actual magnitude of creep associated with such ranking. These data were regressed over time to establish creep growth. Based on discussions with the inspectors and the size of defects likely to be observed in the field, creep values exceeding 2.5 mm were assumed to be a defect of sufficient size to be noted. The time of exposure beyond that, beginning at the 2.5-mm mark, was applied to the local corrosion rate, and the cumulative corrosion was estimated. A specific SoC was assigned to increments of total corrosion.

In all cases, the primary corrosion data were those of coatings applied to steel substrates. Steel corrosion was the primary observation from the field surveys of Army-fielded systems.

The field data included details on the inspection of various part assemblies on specific ground system assets. Part assemblies included items such as “wheels and lugs,” “drivetrain,” “body panels,” and others. Each assembly is a composition of multiple subparts. At the asset level, data collected included the installation location, inspection data, date of manufacturing, last paint date, mileage (limited), and recommended maintenance level (CIC, CIC/Spot Paint, Repaint). For each part assembly on the asset, key data include the part name, the percentage of the area of that part with each of the four grades of SoC, observations of paint delamination, and mechanical paint damage.

Initially, the overarching dataset was reduced in scope to focus on the Family of Medium Tactical Vehicles (FMTV) and Light Medium Tactical Vehicle (LMTV) assets. Although this limitation compressed the size of the dataset, it reduced the complexity of part assembly design that exists within tactical systems, trailers, combat systems, and others. The working dataset still had 2,125 assets and data on over 40,000 parts. The dataset was reviewed, and the primary components noted were identified and segregated into eight groups, each with four-part assemblies (Table ES-1). These parts represent those areas most often noted with more significant corrosion on the assets of interest.

Table ES-1. Key part assemblies.

Group 1 WHEELS AND LUGS CONNECTION POINTS BRACKETS FASTENERS	**Group 5** DOOR FRAME SPARE TIRE MOUNT ROOF HYDRAULIC AND AIR SYSTEMS
Group 2 SUSPENSION DRIVETRAIN BUMPER STEPS	**Group 6** PEDALS DASHBOARD SEATS LATCHES
Group 3 HYDRAULIC AND AIR LINES AND CONNECTIONS LIGHTS AND SIGNALS HINGES	**Group 7** STOWAGE BOXES LADDER ELECTRICAL CONNECTORS AND COMPONENTS HANDLES
Group 4 BODY PANELS CARGO BED FLOORING FRAME	**Group 8** TRUCK BED EXHAUST TURRET RING WELDS

Results and Discussion

The laboratory test data demonstrated considerable differences in the performance of different coating systems. Incubation times for through-film corrosion in outdoor exposure could range from 18 to 60+ months, whereas in accelerated laboratory testing incubation was seen in terms of weeks. After incubation, the systems also exhibited a wide range in the progression of through-film corrosion and thus in the projected visible SoC. The best systems were those with zinc-rich (metal-rich) primers followed by those with the sealed zinc–phosphate coatings. Although there was variability in the case-to-case performance of the organic primer/topcoat combinations, no one particular combinations performed significantly better than any other in testing.

For the creep data, the most significant factor was again the pretreatment. The primer/topcoat combination did not seem to have an effect in corrosion inhibition. The zinc-rich primer was again the superior product.

The analysis of field inspection data focused on initially discerning if any relationship between the data collected and the ultimate maintenance recommendation existed. Initially, the field inspector's analysis focused on the average of all corroded areas reported per specific asset. Although there was a small increase in the average area corroding as the recommended maintenance moved from the least significant (CIC) to the most significant (Repaint), the differences were quite small. Further data manipulation included testing the average corroding area when the corrosion was reported as SoC2, -3, or -4—the more "severe" SoC (S.SoC) versus the more ubiquitous minor SoC1 that appeared on most parts. With a focus on the S.SoC, the average corroding area on reported parts increased by a factor of 2 (nominally) from CIC to CIC/Spot Paint and another factor of 2 in proceeding from CIC/Spot Paint to Repaint. In other words, it appeared that perforation of the paint and subsequent corrosion, which showed signs of metal attack (or worse), were driving the propensity to increase the recommended levels of maintenance.

Asset age was examined and found to be a poor predictor of observed corrosion. This contrasts with laboratory test panels. The finding that age has less predictive power suggests that variables such as asset use or paint quality were more significant than coating performance. Mileage, as an analog for use, was shown to correlate with a shift towards more significant corrosion. Findings of paint delamination appeared as another factor favoring more significant levels of required maintenance. Paint delamination seemed largely independent of findings of S.SoC.

Additional detailed inspection of field assets (beyond the work of the TACOM-sponsored work) was conducted on selected FMTVs. The findings confirmed the variable quality of coating applications on Army ground assets. The data also suggests a significant increase in corrosion due to low film thickness, as well as additional use (and associated mechanical damage) of the assets.

The compilation of the basic findings into a Bayesian Belief Network provides an estimate of the count of part assemblies showing S.SoC. This parameter can be used to suggest the probable categorization of each asset. It also appears that coating delamination factors into the probable maintenance categorization. Currently, it is not possible to determine the probable root causes of the delamination using the existing data. Although multiple expert opinions exist as to such occurrences, there is little data (such as coating breakdown) to provide a basis for modeling and relating these findings to fielded assets.

The model provides a predicted distribution in the SoC on the FMTV/LMTV assets based on age, local corrosivity, mechanical surface profile, pretreatment, and the CARC primer/topcoat system. Additional inputs include materials of construction, part design complexity, mileage, and paint quality.

The model illustrates the difference in projected performance among the different corrosion control coating options. This allows for comparing environmentally acceptable pretreatments and coatings versus legacy systems. The model contains substantial variance in the projected outcomes, largely derived from the variable performance of the coating systems in the standardized testing database. The model and projections would be aided by additional replication of test systems and a basic, root cause analysis of the different failure modes of the test panels. Knowledge concerning the root cause could be added as inputs to the model.

Implications for Future Research and Benefits

This work provides a basis for several future research efforts and benefits to the Army.

- Compared with laboratory testing, Army coating systems on fielded items develop abrasion and other mechanical damage. Steps to improve abrasion/impact resistance would extend the life of the coating and reduce maintenance costs. Such development should begin with assessing the actual forces that may occur on fielded assets to ensure meaningful targets are established.
- In laboratory tests of coating materials, researchers might also consider testing materials applied both within specific target ranges (i.e., ideal performance) and outside of such ranges. The challenges of painting complex parts will result in variations in the paint quality, and it is conceivable that some coating systems will outperform others under these conditions. This variation occurs on actual systems and should be considered.
- Pragmatically, the data show that the use of zinc-rich coatings as a near-universal primer over steel surfaces should reduce corrosion on steel components. Keys to this successful application include ensuring adequate coverage of surfaces and overall paint quality—which can be challenging in all complex parts.
- The modeling work shows that significant variation exists in the performance of "identical" test panels. Additional data needs to be collected and assessed to improve our fundamental understanding of the impacts of the coating process on performance.
- Periodic coating delamination contributes to the appearance of an asset with a failing coating in need of additional maintenance. The root causes of such failures are difficult to replicate in simulation testing.

1. Introduction

Coating degradation and corrosion on U.S. Army ground systems represent significant maintenance costs and correction efforts are labor-intensive, often requiring spot repair and/or repainting. This exposes technicians and the environment to hazards associated with the removal of coating materials from assets (e.g., hexavalent chromium pretreatments, volatile organic compounds, and hazardous air pollutants) and again during the repair and application of new coating materials. Being able to model and predict the corrosion control performance of alternative coatings on Army ground equipment allows researchers to invest in new, less hazardous technologies. This work aids in protecting workers and minimizing environmental hazards by utilizing computer-based simulations versus physical testing. The present work aimed to develop a Bayesian model that associates asset corrosion with the applied coating systems, coating quality, asset design, and operational factors impacting materiel condition. The model provides an initial understanding of the root causes, from which steps can be taken to mitigate the impacts of corrosion. Key research objectives included the following:

- Identify key factors/contributors to coating breakdown on the Chemical Agent Resistant Coating (CARC)[1] system on ground assets.
- Map coating application parameters/variations that have the greatest impact on coating failure and subsequent corrosion.
- Use research and field datasets supplemented by additional testing to develop a predictive model for corrosion degradation on military assets painted with the CARC system.

2. Background

Corrosion and coating degradation result in a significant maintenance burden on Army ground systems. This maintenance burden impacts readiness; corrosion maintenance with corrosion inhibiting compounds (CICs) and coatings creates an environmental impact. The present effort developed a model examining the primary contributors to corrosion observed on Army ground assets. The primary form of corrosion control on these assets is a coating system, derived mainly from the Army CARC systems. The coating failure results in varying degrees of maintenance.

For ground systems, the Army maintains three general approaches to corrosion maintenance: preventative maintenance, spot repairs, and full repainting. Minor corrosion is controlled via the periodic application of CICs. When coatings begin to break down or are no longer providing complete protection, maintenance may incorporate a combination of CIC application and spot painting. Extensive corrosion and coating failure are addressed via complete repainting of the asset.

In support of the Army's Corrosion Prevention and Control program, the Army invests in the identification and testing of protective coating systems, seeking to increase the service life of assets and applied materials. In significant part, many of the materials being evaluated are the result of meeting emerging environmental and regulatory concerns impacting better-performing coating systems. The Army also invests in extensive surveys of ground fleet assets to identify corrosion-prone equipment, systemic problems, and possible solutions. The present modeling program sought to take advantage of both Army investments, combining a series of performance data including the following:

- U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) data concerning the performance of CARC systems. This includes knowledge of the development of the original and current CARC systems and exposure testing.
- Field inspection data from the U.S. Army Tank-Automotive and Armaments Command (TACOM) sponsored ground vehicle survey efforts. This program began in 2015. At the beginning of this effort, these inspections included nominally 20,000 assets, identified over 300,000 parts with corrosion and coating damage, and contained more than 300,000 photographs of corrosion and coating damage on these parts.

The laboratory data describes the performance of coatings and materials under controlled and monitored conditions. Coating loss and corrosion on actual assets represent the results of uncontrolled conditions experienced in service.

Establishing the relationship between asset condition and "laboratory-expected" coating performance considered additional factors including the following:

- The actual exposure environment.
  - The corrosivity of equipment stationed in locations prone to high time of wetness (TOW) or in close proximity to salt water is expected to experience more rapid corrosion damage than equipment located in an arid environment.
  - TOW was recorded in hours and categorized into high, medium, and low. Proximity to saltwater effects were categorized as yes or no.
- The use of the equipment.
  - Inherently, some assets in training and operational missions are used more regularly than others. This places a larger strain on these corrosion protection measures due to the impact from road debris, cargo carrying, Soldiers entering/exiting the vehicle, among others.

    - Furthermore, in the operation of equipment, specific components can be subjected to more physical damage, which exacerbates corrosion tendencies.
- Part complexity and quality of paint application.
    - Army equipment is fabricated from multiple subparts, each with its own physical complexity.
    - It is more difficult to achieve a high-quality paint system on complex, bolted, or faying surfaces compared with flat surfaces, which are more representative of a "laboratory test panel."

Linking the laboratory results and the field observations was a key challenge in the program. This effort was complicated because the laboratory data are gathered via reference to standard American Society for Testing and Materials or military specification procedures. Observations in the field data were based on Stages of Corrosion (SoC) ratings. Army ground equipment corrosion is described by SoC ratings (Figure 1) as outlined in TB 43-0213.[2] Data concerning materiel condition is gathered as part of standardized inspections, and the results of the inspections are a basis for recommended remedial preservation action.

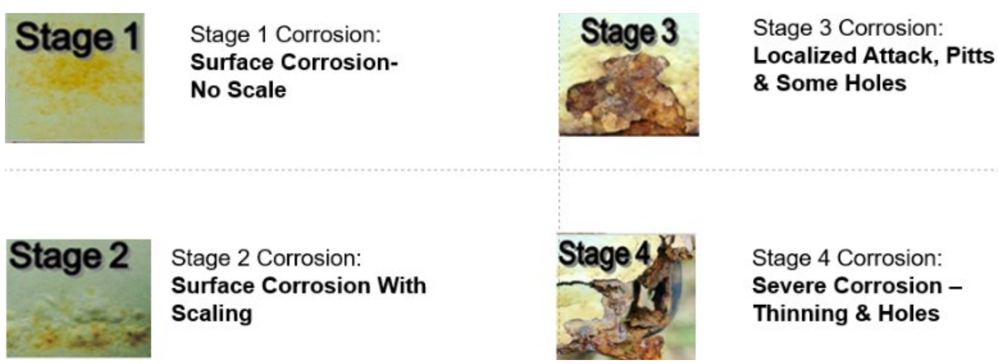

Figure 1. The SoC.

The maintenance action used to abate Stage 1 corrosion conditions is typically the application of CICs. Stage 2 and Stage 3 corrosion can require surface preparation to remove degraded coating and corrosion, metal repair to restore damaged metal, paint application, and the application of CICs. Stage 4 corrosion requires part repair/replacement in addition to coating of the part. Maintainers evaluate the coverage and location of such SoC and recommend the appropriate maintenance action. These repairs require personnel (Soldiers through depot-level maintainers) to apply the materials during open-air application (e.g., CIC application and spot painting by owning units) or in controlled application of coatings and other chemicals in industrial facilities. Reducing the need to perform maintenance, painting, and avoiding the use of more hazardous corrosion inhibitors is a beneficial outcome of this program, as is understanding how alternative systems aid in these goals to maximize performance/minimize environmental emissions.

3. Methods and Materials

3.1 Model Process

The process was used to evaluate how Bayesian modeling could be used to explain the performance of the present Army CARC systems applied to ground assets. Bayes' theorem is a causal statement where "*A*" is a cause of "*B*," and where "*B*" takes the role of the observable effect of "*A*," which typically cannot be observed itself. Mathematically, it is typically expressed by the equation

$$P(B \mid A) = \frac{P(A \mid B) \cdot P(B)}{\sum_{b \epsilon \mathcal{B}} P(A \mid b) \cdot P(b)} \qquad (1)$$

Equation 1 relates the probability that event "*B*" occurs given that "*A*" has occurred to the likelihood of "*A*" being associated with event "*B*" and the probability of "*B*" divided by all states that would cause "*A*." *A* and *B* are finite state vectors having values $a = a_1, a_2,, \ldots, a_n$ and $b = b_1, b_2, \ldots, b_n$. Note that the denominator is summed over all the state values of the hypothesis, *B*.

Consider a simple example. Let P (B|A) represent the probability of rain ("B") given observations of black clouds ("A"). Let us assume that the relationship P (A|B), the appearance of black clouds associated with rain, is true 70% of the time. However, we only have rain in general P (B) 20% of any day. We can also have black clouds on days without rain 30% of the time. Using Equation 1,

$$\mathrm{P(B|A)} = \frac{70\% \times 20\%}{70\% \times 20\% + 30\% \times 80\%} = 37\% \,.$$

Although we may casually associate the onset of rain with signs of black clouds, the fact that we also can have black clouds on days without rain, and that days without rain are common, the occurrence of rain suggested by visible black clouds is only true 37% of the time.

However, the relationship representation in Equation 1 is incomplete and perhaps somewhat misleading. A more formal expression is as follows:

$$P(B \mid A, I) = \frac{P(A \mid B) \cdot P(I \mid B) \cdot P(B)}{\sum_{b \epsilon \mathcal{B}} P(A \mid b) \cdot P(I \mid b) \cdot P(b)} \,. \qquad (2)$$

This expression includes the context of background information, "*I*." The inherent justification in using Equation 1 over the more complete Equation 2 is the assumption that the background information *I* has no unique influence on the inference (P|A,I) and therefore can be excluded from the analysis. If a variable found in *I* impacts the result, then the Bayesian model itself is incomplete.

In the context of hypothesizing the performance of a CARC system, a Bayesian Belief Network (BBN) is depicted by Figure 2 using Equation 1.

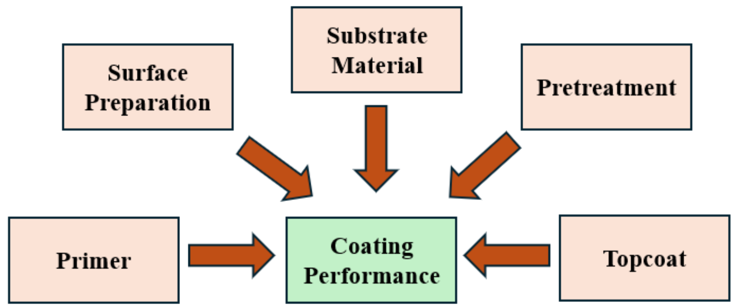

Figure 2. BBN relational model for coating system performance as a function of independent variables.

Of course, as explained above, Equation 1 and Figure 2 present a naive viewpoint, and the more complete BBN should be represented by Equation 2 and Figure 3, which includes "Everything Else" that might influence the performance.

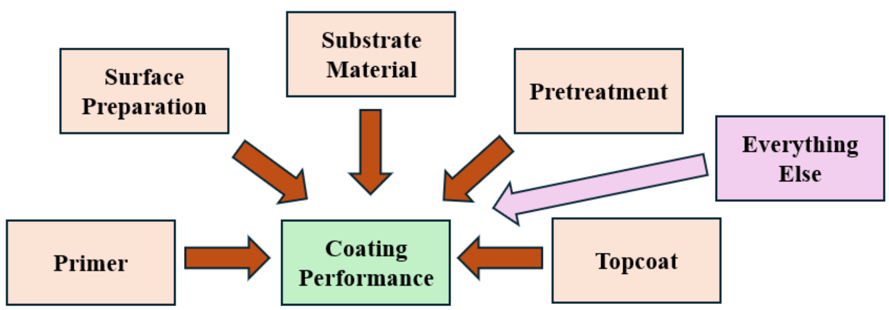

Figure 3. Expanded BBN relational model for coating system performance as a function of independent variables.

In the case of CARC performance in the field, "Everything Else" may be the dominant influence on the outcome. Even in a controlled laboratory measurement of coating performance, external factors can cause biases and variances in the results: for example, quality control in application of the various steps in the applied coating method, and environmental issues associated with outdoor coupon tests.

The model is based on a BBN. In the BBN, outputs ("children") derive from two or more inputs ("parents"). A Conditional Probability Table (CPT) establishes the relationship between the inputs and the output as encoded by Bayes' theorem Equations 1 and 2. The CPT defines a likelihood of specific states of the output variable based on the states of the input variables. Figure 4 is a simple schematic

BBN with "Surface profile" as one node and the Pretreatment, Primer, and Topcoat choices combined as the "Paint System" node, resulting in two inputs, each with two possible states. The output of the network is the projected coating life with binary states of short life and long life. The only difference between the left and right side of the example is the state assignment of the "Surface profile" node as the ratio of abrasive blasting to grinding: 10% to 90% on the left and 90% to 10% on the right.

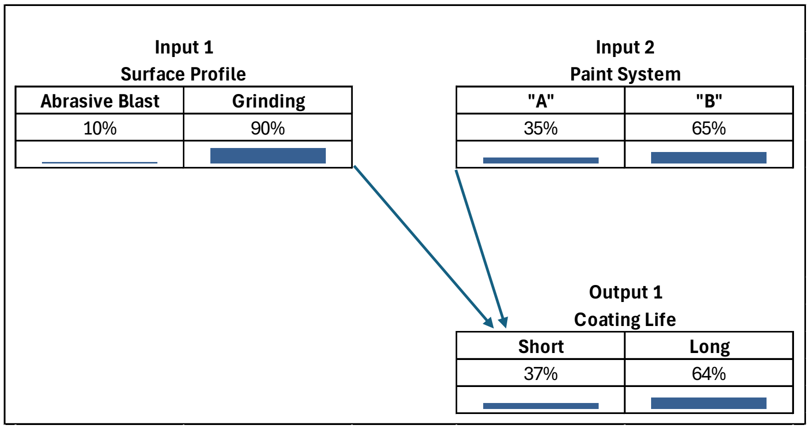

Figure 4. The BNN relates coating life to surface preparation and paint; 10% abrasive blast/90% grind (left) and Paint Systems A and B (right).

Table 1 provides a CPT for the relationships between the two inputs. With two inputs, each with two states, 2 × 2 (i.e., 4) likelihoods are needed to define the proportion of each output state.

Table 1. CPT for parameters of surface preparation and paint system.

Surface profile	Paint system	Likelihood based on input possibilities	
		Short life	Long life
Abrasive blast	A	0.25	0.75
Abrasive blast	B	0.15	0.85
Grinding	A	0.45	0.55
Grinding	B	0.35	0.65

On the left side of Figure 4, the model projects that 37% of the outcomes will be a "short" life. Inspection of the CPT shows that a "short life" will occur with each of the four possible input combinations, each with its probability. The sum of these combinations, each resulting in a short life, provides the expected probability of a short life. Table 2 shows this math with the last column rounded to whole number percentages.

Table 2. CPT with input state probabilities to derive probability of short life.

Input 1	Input 2	Probabilities		Short-life likelihood	Input 1× Input 2× likelihood
		Input 1	Input 2		
Abrasive blast	A	10%	35%	0.25	2%
Abrasive blast	B	10%	65%	0.15	1%
Grinding	A	90%	35%	0.45	14%
Grinding	B	90%	65%	0.35	20%
. . .	. . .	. . .	. . .	. . .	37%[a]

[a]Total

For the development of the subject model, defining the key input parameters and the CPT associated with the outputs from various combinations of the inputs is crucial. The CPT may be derived from data analysis or may be a subject matter expert consensus. The program sought to utilize inputs for which data was available to establish relationships.

3.2 Analysis of ARL Coating Test Data

A "top-down" to "bottom-up" approach (Figure 5) was used in the program. ARL (and other) testing data derived from test panels provided American Society for Testing and Materials (ASTM) (or ASTM style*) ranking information on the expected performance of coating systems. ARL captures corrosion data utilizing the ratings systems given in ASTM D1654[3] and TT-C-490[4] for scribe corrosion and blistering, respectively. The field database collected by TACOM contains collected SoC data along with limited data concerning the history of the items inspected.† The laboratory data had to be "converted" to an expression of SoC to allow for comparison to the field data. The field data comprised a range of SoC conditions on various asset components, and assumptions had to be made to associate the observed corrosion with the root causes suggested by the laboratory data.

* Some data used MIL-SPEC ratings, which were similar in structure to ASTM ratings but had different criteria for their values.
† The field database was not intended as a research tool but as a "snapshot" of the corrosion condition of fielded Army materiel.

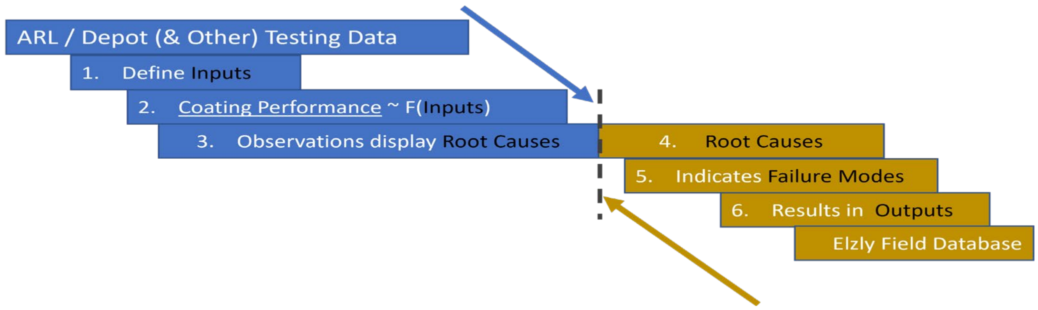

Figure 5. Top-down and bottom-up approaches.

The majority of the field inspection data involved corrosion related to degradation of steel substrates with visible rusting. The analysis of the ARL dataset focused on coating system performance over steel substrates.

ARL provided a large dataset showing the performance of both standard and novel CARC systems. Much of the data was used to evaluate various pretreatment materials over steel and aluminum substrates, in conjunction with common CARC epoxy and polyurethane organic primers and topcoats. The panels were prepared by trained technical staff to evaluate specific coating system combinations. Typical combinations of interest included forms of surface profile (mill finish or abrasive blasting), followed by surface pretreatments, and a two-coat epoxy/urethane coating system derived from the options for CARC under MIL-DTL-53072.[1]

Panel sets included both scribed and unscribed panels exposed in cyclic corrosion test chambers in accordance with GMW14872[5] and natural marine environment exposures at Cape Canaveral Space Force Station (CCSFS). Data on scribe creep and general panel degradation (blistering) were obtained in accordance with ASTM D1654[3] and the blister rating scheme presented in TT-C-490.[4] Table 1 was obtained following Outdoor data collection and was typically gathered over 3-month intervals for periods as long as 48 months, with some exposures extended to 60 months. Indoor data was collected every 10 cycles, with each cycle comprising 1 day.

The data of interest in this program are those utilizing the common pretreatment of zinc phosphate on steel surfaces before application of the organic coatings. Zinc phosphate rinses with either hexavalent chromium or chrome-free materials were included. Zinc-rich primers and controls (acting as a pretreatment) were also included as were additional inorganic pretreatments. The nomenclature identifying these pretreatment materials is intended as a generic identifier (as per the ARL dataset) to understand the benefits of modeling, and the indicators (e.g., chrome-free rinse) should not be interpreted as applicable to all pretreatments that may share a similar description.

Common organic primers included MIL-DTL-53022[6] and MIL-PRF-23377.[7] Common topcoats included MIL-DTL-53039,[8] MIL-DTL-64159,[9] and MIL-PRF-85285.[10] The primary datasets of interest are based on coatings applied and tested originating in 2011–2014. These dates correspond to the average age of the fielded assets, which is also part of the modeling process.

The analysis focused on data from the natural marine weathering site at CCSFS; the data from a natural weathering site seemed more applicable for predicting specific rates of coating degradation than results from accelerated corrosion test chambers. Accelerated corrosion testing is utilized primarily in material qualification or comparative material testing for quick validation of coating application, but it is more difficult to relate to actual world exposures given the static condition parameters within the chamber versus dynamic outdoors conditions. Researchers for this project have found that accelerated corrosion testing is best suited for identifying relative performance between candidate systems, with increased duration in such tests improving confidence in that performance. The correlation of the duration of testing and length of service cannot be readily identified due to the variables associated with the design and manufacture of Army ground equipment platforms.

The data concerning through-film corrosion represented flat, continuous surfaces on an asset without defects. The test data from scribed panels modeled the performance expected at film defects or edges. This later data was also extended to model coating performance on complex surfaces with welds, fasteners, and complex shapes on the surface.

3.2.1 Coating Failure via Through-Film Breakdown

Through-film breakdown is a type of corrosion that occurs over time, emanating through a previously intact, corrosion-free coating. Through-film corrosion begins with small, individual "spots" of corrosion (red-rust on steel), and this result was observed using the visual inspection method. Over time, the density of such corrosion increases, or individual spots may combine to form large semicontinuous areas of corrosion.

Observations of through-film corrosion in the ARL exposure data on unscribed panels were modeled by two phenomena: a time to initial breakdown (a.k.a., "incubation time") and corrosion growth. In the present analysis, these two events were considered independent for simplicity. For each unique combination of material, surface profile, pretreatment, and two-coat system, ARL exposed a range of replicate panels. The panel count ranged from 3 to 12 samples for a unique coating combination, but a set of panel replicates was most commonly 5. Although the panel sets had consistent substrate, surface profile, pretreatment, and organic coating parameters, they may have been prepared by different staff, months apart. In this sense, they represent a variable process that will also occur in painting actual assets. This is an example of Everything Else from Figure 3. The relevant ratings for this portion of the project are the TT-C-490[4] ratings (Table 3) recorded every 3 months for a duration that ranged between 6 and 60 months (depending on early removal due to failure or environment). Not every panel has data for each inspection, and some panels are removed from testing after significant failure.

Table 3. Ratings for unscribed panels.

Area failed (%)	Rating no.
No failure	10
0 to 1	9
2 to 3	8
4 to 6	7
7 to 10	6
11 to 20	5
21 to 30	4
31 to 40	3
41 to 55	2
56 to 75	1
>75	0

The incubation time for a specific panel is the month in which the panel first indicated a 9 rating; previously, the data would have been a 10 rating, the best possible rating of "no failure." If the first rating after a 10 rating was anything other than a 9, for example, an 8 or 7, the incubation time was considered interval censored* between the time of the last 10 rating and the month of the present rating, which was other than 9. Panels that remained at a 10 after the exposure were considered right-censored data, wherein the incubation month was beyond the last reported time. The incubation analysis grouped the data for each unique coating system combination of substrate material, surface profile, pretreatment, and primer/topcoat. The distributions of incubation times for the group were fit to a Weibull distribution, providing a scale and shape factor for the data via Minitab 21 with Maximum Likelihood Estimates.†

The projections for coating failure after the incubation time were developed using the following methodology:

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* In statistics, interval-censored data occur when you do not know the exact value of an event or measurement, but you do know it happened within a specific time range or interval.

† Instances in which the datasets did not provide a distribution, that is, the panels all performed the same, the incubation time was assumed as the average of the intervals over which the rating first decreased to a 9 rating.

- Arranging the coating condition rating data to reflect the exposure time after the inspection interval, where a rating of less than 10 was noted. This first inspection interval occurred 6 months after the incubation; hence, it became the 6-month rating. Depending on when the first breakdown was noted, the growth dataset may contain from one to seven datapoints.
- Table 4 shows an example of a projection of a coating failure rate with respect to incubation interval. The raw data suggests that the incubation period for this example was 18 months. The observation occurred 6 months after the last rating of 10 and became a baseline for damage growth. The observations for actual exposure times of 24, 30, and 36 months become the growth data representing 12, 18, and 24 months of exposure, respectively.
- These scribe corrosion ratings were linearly regressed to project the expected scribe rating.* After comparing the actual panel scribe rating post incubation with the projected panel scribe rating, reasonable agreement for this example panel was revealed, demonstrating the ability to extend the scribe rating to 30 and 36 months post incubation.
- Overall ratings were established for each panel of a particular coating system combination. If there was only a single rating or the same rating after incubation, this rating was carried forward in any projections without alteration.
- Finally, this rating was converted to an SoC rating.
    - Overall ratings of 9 or 8 were expected to be of such minimal corrosion as not to be noticed in an actual asset field inspection. These were assigned a No Corrosion (NoCorr) indication.
    - A 7 or 6 rating was equated to a Stage of Corrosion 1 rating (SoC1).
    - A 5 or 4 rating was considered a Stage of Corrosion 2 rating (SoC2).
    - A 3 or 2 rating was assigned a Stage of Corrosion 3 rating (SoC3), and anything less than a 2 was assigned a Stage of Corrosion 4 rating (SoC4). These allocations were made in consultation with the field inspection personnel.
- The projections were conducted for a total of 72 months of growth, at 12-month intervals. This was completed for all test panels of a particular system. They did not all behave similarly and therefore presented a range of SoC indications for the same exposure time.
- A raw count of the observations of NoCorr, SoC1, SoC2, SoC3, and SoC4 were performed and normalized as a percentage of the number of panel

* Various regression models other than linear fits were also examined. The linear fit proved a reasonable approximation for most panels evaluated.

observations. This dataset provides the expected distribution of corrosion observations on the coated panels after the incubation period.

Table 4. Example of projections of coating failure growth rates.

Raw data						
Months	6	12	18	24	30	36
Panel rating	10	10	9	8	8	7
Post incubation						
Months	6	12	18	24	30	36
Panel rating	9	8	8	7	[a]	[a]
Linear fit of post-incubation data						
Months	6	12	18	24	30	36
(projected) panel rating	8.9	8.3	7.7	7.1	6.5	5.9
SoC	NoCorr	NoCorr	SoC1	SoC1	SoC1	SoC2

[a] No data reported beyond the 36-month exposure; project fit based on linear fit of data available.

The data for the incubation period and subsequent growth were then combined to establish the expected distribution in corrosion observations for a given coating system over time. This was an iterative process including the following steps:

- A formatted table covering the observation years 1 to 6 (12–72 months). Appendix A, Table A-1 provides an example of the table and calculations. For each total time of exposure, a proportion of the panels would have exceeded the incubation time. This proportion is based on the Weibull distribution of incubation times for that system.
- In each successive total exposure year, some panels may have exceeded the incubation in the previous year and others in the present year. Using the incubation estimates, the proportion of coating degradation occurring in each year was estimated.
- For each discrete timeline interval in Table 4, the incubation time is assumed to be exceeded at the beginning of the year, and growth occurs for the remainder of the year. The proportion of the panels post incubation in year 1 is assumed to grow due to corrosion for 1 year. At 2 years of total exposure time, the same proportion was assumed to have grown for 2 years. The proportion of the population exceeding the incubation in year 2 was assumed to have 1 year of growth in year 2. This process was repeated for each set of total exposure times.
- The expected distribution of the various SoC for each cumulative growth time was applied to each incubation time set. By multiplying these values by the proportion of the population represented by the specific incubation time set, we obtain the distribution of the expected observations of the post-incubation coatings. These can be summed up to provide part of the overall expected distribution. The proportion of the population not yet past the incubation time was added to the NoCorr proportion of the data to complete

the representation of the population. See Table A-2, which summarizes these values for years 1 and 2 of the data in Table A-1.

This same process was repeated for all coating systems of interest in the modeling effort.

3.2.2 Coating Failure via Creep at an Intentional Scribe

Coating failure initiated by a surface defect that extends down to the substrate material and can migrate under the coating is described as "creep." Creep is a measure of the advancement of corrosion away from an induced coating surface defect over time. In controlled laboratory experiments, creep is induced by utilizing a tungsten carbide scribe to make a set of lines oriented as an X that penetrate through the paint surface down to the metal substrate, thereby simulating an event where the coating on a fielded item has been compromised, such as from a scratch, but in a worst-case scenario.

ARL provided creepage data for panels of different coating systems based on exposure observations at the CCSFS test site. The data were based on the ASTM D1654[3] procedure A, which converts distance measurements into a numerical rating scale, ranging from 0 to 10. This data was collected over 42–48 months, in 3-month intervals. The present model assumes growth from initial exposure, with no incubation time. Table 5 shows the scribe creep ratings, per ASTM D1654.[3]

The scale in ASTM D1654[3] (Figure 6) represents creepage at the scribe in sequential ranges of distance (both inch and millimeter). For analysis, a conversion equation was developed relating the ASTM 0–10 rating to the maximum creepage for a specific range. For example, a number 6 rating refers to creep of 1/16 to 1/8 inch. For the present purposes, the analysis assigned the maximum of the range to the numerical value; a number 6 rating represented 1/8-inch creep. For number 10 (0-inch creep), a value of 1/128 inch was assigned to avoid a 0 (undefined 1/creep) value; this is 1/2 of the maximum number 9 range of 1/64 inch. For a number 0 ("zero") rating, the creep was assumed to be 1 inch. The rating versus 1/creep was plotted and regressed (Figure 6), and the equation was applied to the ASTM ratings to produce an estimate of the physical creep.

Table 5. Scribe creep ratings.

Representative mean scribe creepage		
Millimeters	Inches (approx.)	Rating (no.)
0	0	10
0–0.5	0–1/64	9
0.5–1.0	1/64–1/32	8
1.0–2.0	1/32–1/16	7
2.0–3.0	1/16–1/8	6
3.0–5.0	1/8–3/16	5
5.0–7.0	3/16–1/4	4
7.0–10.0	1/4–3/8	3
10.0–13.0	3/8–1/2	2
13.0–16.0	1/2–5/8	1
>16.0	>5/8	0

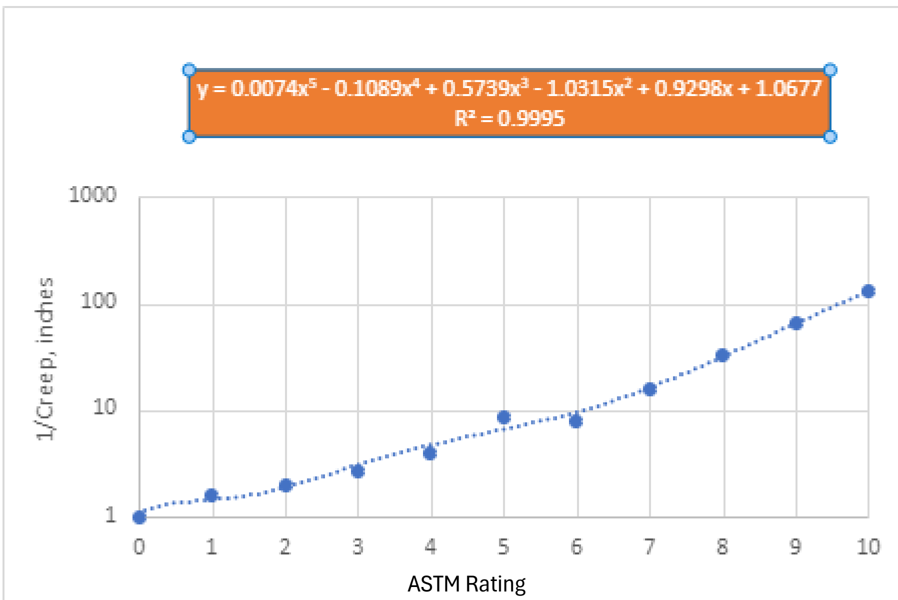

Figure 6. Regression of 1/creep vs. ASTM D1654[3] rating.

For primary systems of interest, the raw data for each panel was regressed to project the rating to a total of 72 months (6 years). The regression used the recorded creep ratings data to establish the fit via a power law approximation: creep = A × time^B. For each panel, "A" and "B" values were determined, and estimates of creep were calculated for periods beyond the end of the actual recorded data. Typically, estimates were created for 60, 72, and 84 months of exposure.

For each panel corresponding to a particular coating system (surface profile, pretreatment, primer, and topcoat), a count of panels with a creep above 0.1 inch

(2.5 mm) was completed for each year of exposure (1–6 years).* Coating systems ranged from 3 to 11 samples per set of unique combinations, a small dataset.

For each year of exposure, the bare steel at the scribe, or steel subsequently exposed as the coating creep occurred, was assumed to corrode at the local annual corrosion rate. Based on mass loss data collected at the CCSFS from 2010 to 2018, covering periods ranging from 0.5 to 3 years, the average corrosion rate is 2.3 mils/year (59.5 µm/year).

Provided with the proportion of samples with creep above 0.1 inch and the annual corrosion rates, the cumulative corrosion at defects could be estimated. If the projected corrosion creep was less than 0.1 inch, the defect was assumed to be not corroding (because the minor defect would not be noted in the inspection, even with a slight amount of corrosion of the underlying metal).

If the cumulative corrosion was less than 5 mils (125 µm), nominally the thickness of a "sheet of paper," the corrosion was assumed to be SoC1. Between 5 and 10 mils (125 and 250 µm), corrosion was assumed to be SoC2. Beyond 10 mils (250 µm), the corrosion was referred to as SoC3^{+} (SoC3 and SoC4). With a local corrosion rate of 2.3 mils/year, SoC1 occurred in previously bare areas between 0 and 2.1 years with a creepage of >0.1 inch. SoC2 occurred between 2.1 and 4.2 years, and SoC3^{+} occurred at 4.2 years and greater.

Appendix A, Table A-3 shows a summary of data for abrasive blasted steel, without any pretreatment, utilizing a MIL-DTL-53022[6] primer and a MIL-DTL-53039[8] topcoat. The dataset consisted of 11 samples. The following illustrates the condition of these samples and estimations of corrosion loss and corrosion rate:

- Year 1
    - 3 of 11 (27%) exceeded 0.1 inch (2.5 mm) of creep, with a corrosion rate of 2.3 mils/year, resulting in a SoC1 (<5 mils total corrosion).
    - 8 of 11 (73%) were rated as NoCorr.
- Year 2
    - 11 of 11 (100%) exceeded 0.1 inch (2.5 mm) of creep, with all actively corroding at 2.3 mils/year.
    - 27% cumulative corrosion loss of 4.6 mils (119 µm), still resulting in SoC1. This was the area failing initially in year 1, yet still below the SoC2 threshold.

* A creep of 0.1 inch (2.5 mm) represents a complete creep across the scribe of 0.2 inch (5.0 mm). The intent was to tie the creep data from panels to probable visual observations on the actual Army ground assets. Based on discussion with the asset inspection teams, 0.2 inch was considered a reasonable estimate of the minimal width that would be noted in the survey process.

   - 73% corrosion loss, corroding at 2.3 mil/year, resulting in a SoC1.
- Year 3
   - 27% cumulative corrosion loss of 6.9 mils (178.5 µm), resulting in a SoC2.
   - 73% cumulative corrosion loss of 4.6 mils (119 µm), resulting in a SoC1.

For each observation year, the percentages of the population in each corrosion category were summed, as discussed above for through-film corrosion. This effort was repeated for each coating system of interest.

The results from the scribe analysis also provided a basis for estimating the SoC on complex surfaces compared with flat panels with an intentional defect. Complex surfaces with structures normal to the general surface or inherently creating crevices on the surface are more likely to have coating defects and corrode more rapidly (Figure 7).

Figure 7. Scribe panel vs. complex panel, 40 cycles GMW14872,[5] CARC.

The impact of complex surfaces was derived from a work examining the analysis of exposure data from a large panel set of both flat and complex panels exposed to GMW14872[5] cyclic corrosion testing.* Panels from 40, 80, and 120 cycles were evaluated for SoC across various CARC systems. The average increase in the population with a SoC2, SoC3, or SoC4 rating was nominally 50%, considering scribes on flat panels versus complex surfaces in the same exposure. This factor

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* Accelerated Corrosion Expert Simulator (ACES), GCAS, Inc., Contract No.: W56HZV-09-C-0046, 2009. https://www.dau.edu/sites/default/files/Migrated/CopDocuments/Accelerated%20Corrosion%20Expert%20Simulator%20ACES.pdf

was applied to the projected scribe data results to reflect the outcome for complex surfaces. The factor is higher early in the cyclic exposure testing, reflecting the more rapid onset of corrosion on the complex surfaces, and tends to decrease with additional test cycles. The actual range was 66% to 32%. However, the 50% average value was used in the present model.

The data from the accelerated testing was used in this analysis to reflect the difference in performance between defects on flat surfaces versus those on more complex surfaces with channels, fasteners, and welds. The dataset represented the best available dataset to compare the different surface conditions.

3.3 Army Asset Inspection Process

Teams of up to eight inspectors performed the Army asset inspection process and traveled to different posts for a 1- to 2-week period. Each day, the inspection team would be assigned to specific locations to inspect ground assets for corrosion damage. All inspections used in this effort are based on visual data observation and collection. Inspectors were all similarly trained and given the same guidebook to interpret visual observations. The visual inspection process was driven by an Elzly data collection software tool, running on a series of Apple iPads, to maximize uniformity and consistency. The Army ground vehicle survey data contains identifying information concerning each asset included in the inspections. Key data per asset includes the following:

- Installation Location
- Inspection Date
- National Stock Number (NSN) and Bumper Number
- Date of Manufacturer (DoM)
- Last Paint Date (if noted)
- Inspector Name
- Family of Vehicles
- Recommended Maintenance Level (CIC, CIC/Spot Paint, Repaint)
- Part Name
- Stage(s) of Corrosion Observed
- Percentage of Area with Particular Stage of Corrosion (in 5% increments)
- Paint Delamination
- Mileage
- Mechanical Paint Damage

For the present program, the analysis focused on the Family of Medium Tactical Vehicles (FMTV)/Light Medium Tactical Vehicle (LMTV) vehicles. A total of 2,125 assets were inspected. Table 6 shows the proportion of FMTV variants (55%) and LMTV (45%) that comprise the top 90% of these assets.

Table 6. Assets in the field data analysis.

NSN	Family variant nomenclature	Population (%)
2320-01-549-8610	TRUCK, CARGO, M1083A1P2 WO/W	15
2320-01-447-3890	M1083A1 (MTV) TRUCK CARGO W/E	15
2320-01-549-8577	TRUCK, CARGO	12
2320-01-447-6343	M1078A1 (LMTV) TRUCK CARGO 2.5 TON 4X4 W/E	9
2320-01-552-7759	TRUCK, TRACTOR	6
2320-01-447-3893	M1088A1 (MTV) TRUCK TRACTOR W/E	4
2320-01-552-7773	TRUCK, CARGO, M1085A1P2 WO/W	3
2320-01-354-3385	M1078 (LMTV) TRUCK CARGO 2.5 TON 4X4 W/E	3
2320-01-552-7787	TRUCK, DUMP, M1157A1P2 WO/W	2
2320-01-552-7745	TRUCK, VAN, M1079A1P2 WO/W	2
2320-01-447-3884	M1083A1 (MTV) TRUCK CARGO W/E W/W	2
2320-01-447-3887	M1084A1 (MTV) TRUCK CARGO W/MHE W/E	2
2320-01-552-7781	TRUCK, VAN	2
2320-01-549-8565	TRUCK, CARGO, M1083A1P2 W/W	2
2320-01-447-4938	M1079A1 (LMTV) TRUCK VAN 2.5 TON 4X4 W/E	2
2320-01-447-3882	TRUCK, CARGO	2
2320-01-447-3889	TRUCK, CARGO	1
2320-01-549-8611	TRUCK, CARGO, M1078A1P2 W/W	1
2320-01-447-3888	M1078A1 (LMTV) TRUCK CARGO 2.5 TON 4X4 W/E W/WINCH	1
2320-01-447-3892	M1089A1 (MTV) TRUCK WRECKER W/W W/E	1

The two family types were combined to increase the data points for model development. FMTVs are conceptually similar to tactical vehicles and larger than the LMTVs, with twice the tonnage payload capacity. There are significant mechanical differences to accommodate different tonnage ratings, including a stronger chassis and frame, heavy-duty suspension, more robust axles, often with dual rear wheels or tandem axles to distribute weight, stronger braking systems, and larger engines and gearboxes. FMTVs have a 6 × 6 drive configuration versus the LMTV 4 × 4 design, and the cargo bed platform is larger, stronger, and more reinforced.

The DoM was obtained from the data plate. Often, the last painting date was not stenciled on the asset leaving it mainly unknown in the dataset. Herein, age refers to the asset age based on the inspection date, minus the DoM. Figure 8 shows the distribution of ages identified for 2,078 of the 2,125 assets (some data plates were not accessible).

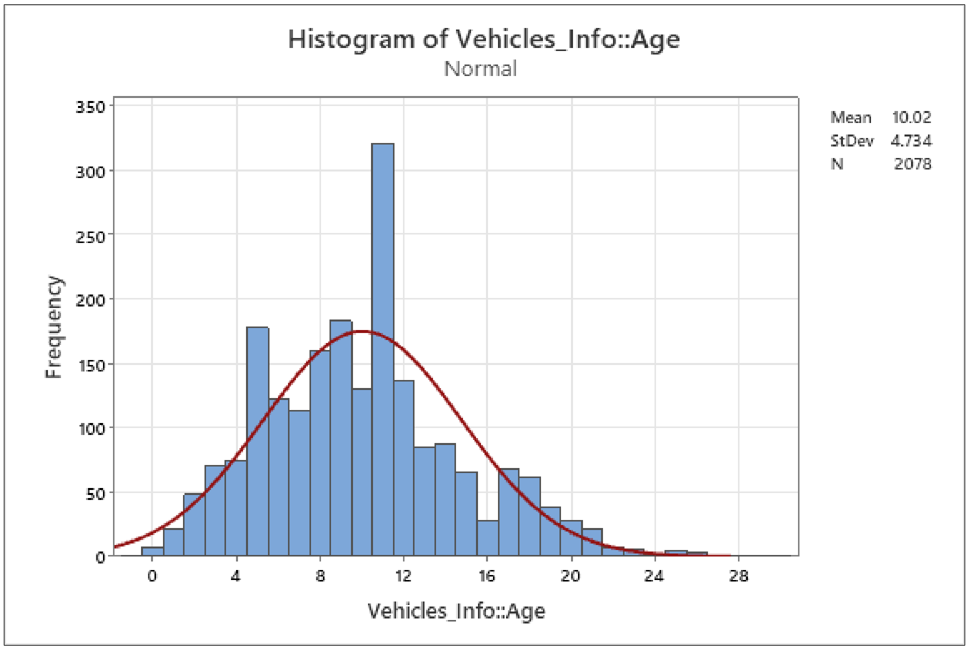


Figure 8. Distribution of asset ages in the dataset.

Each inspection divided an asset into seven views: front, back, driver side, passenger side, roof, underbody, and interior. In each view, inspectors noted the deteriorating parts. "Parts" refer to an assembly of sub-parts to create specific structural and functional components. Although a typical truck has over 4,000 individual parts that comprise hundreds of assemblies, the present inspection focused on 32 assembled components, which are colloquially referred to herein as parts.

Table 7 shows the part names divided into eight groups. Appendix B provides representative pictures of the subject parts.

Table 7. Key part assemblies.

Group 1	**Group 5**
Wheels and Lugs	Door Frame
Connection Points	Spare Tire Mount
Brackets	Roof
Fasteners	Hydraulic and Air Systems
Group 2	**Group 6**
Suspension	Pedals
Drive Train	Dashboard
Bumper	Seats
Steps	Latches
Group 3	**Group 7**
Hydraulic and Airlines and Connections	Stowage Boxes
Mirrors	Ladder
Lights and Signals	Electrical Connectors and Components
Hinges	Handles
Group 4	**Group 8**
Body Panels	Truck Bed
Cargo Bed	Exhaust
Flooring	Turret Ring
Frame	Welds

Each part with corrosion or another form of damage in each of the seven views was rated. Corrosion damage was rated using the previously referenced SoC (Figure 1). A part may show none, one, or more of the four SoC. Figure 9 shows how all forms of corrosion may occur on a single particular part. The extent of each SoC for a part was noted in 5% increments. The data was obtained via a coarse scale and did not distinguish between a part with 0.1%, 1%, or 5% of the area showing a specific form of an SoC—all would be listed as having 5% of that SoC.

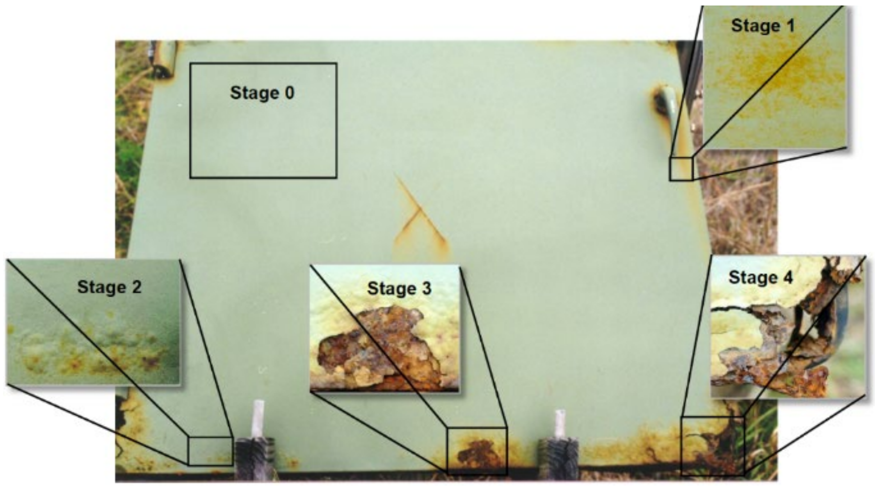


Figure 9. Visual representation of SoC.

Paint delamination and paint mechanical damage was listed as a "Yes/No" observation. Paint delamination was further defined with the location of the delamination, that is, delamination at the substrate versus intercoat delamination between topcoat and primer.

Mileage was not often noted for the assets. This metric was challenging to obtain, because many assets use digital odometers that are not visible unless the truck is turned on. Locked doors also limited access. As noted below, impacts of mileage were studied independently by including items with any mileage data for any asset in the database.

After a 15- to 30-min inspection per asset, the inspector made a recommendation for further repair. Relevant to the modeling are recommendations for maintenance via CICs alone, spot painting followed by CICs, and repainting. The maintenance recommendation was based on an assessment of the comprehensive condition of multiple parts and conditions on the vehicle—it was not a recommendation based on a fixed algorithm. This is a common experience where the inspector is considered a trained expert in making such recommendations.

To evaluate paint quality on typical Army assets, more detailed, instrument-based inspections were performed. An engineering inspection was conducted on 16 FMTVs at the Logistics Readiness Center/maintenance facility at Joint Base McGuire–Dix–Lakehurst (Fort Dix, New Jersey). The FMTVs ranged in age from <1 to 15 years old. The survey included collecting data on different parts of the vehicle including coating thickness, coating holidays, and overall vehicle condition. A team collected the data starting with a walk-through to discuss data collection procedures and locations. The intent was to locate specific areas on each asset (a.k.a., parts) for assessment. Eleven parts were identified as follows:

- Suspension
- Light and Signs (Front)
- Body Panel (Driver)
- Body Panel (Passenger)
- Cargo Bed (Driver/Rear)
- Stowage Box (Driver)
- Stowage Box (Passenger)
- Welds (Front)
- Roof (Top)
- Body Panel (Rear)
- Hatch (Top)

For each item, the assessment included the following data collection:

- Surface magnetic (yes/no)—to determine if the part is ferrous or nonferrous
- Estimate (percentage) of the complex surface that is paintable—extent of the part complexity that would limit the ability to properly paint via conventional spray paint application
- Rust from crevices (yes/no)—corrosion occurring at mating interface of subcomponents comprising the complete part
- Water trap (yes/no)—an area that would hold water
- Abrasion on coating (yes/no)—signs of abrasion
- Delaminated coating (yes/no)—signs of delamination
- Coating dry film thickness (DFT) (see below)
- Holiday density (see below)
- SoC (see below)

Chalk markings were added to each part to promote uniform locations for data collection on the different assets. On each part, the inspector obtained 6–12 DFT readings at a density of approximately 0.25 ft^2/spot reading. This is a much higher density of readings compared with the quality control requirements required per TB 43-0139,[11] which calls for 10 measurements per repainting individual components or 20 measurements per complete painting of "larger items." DFT readings were made using PosiTector 6000 and Elcometer 456 with appropriate calibration and adjustments before use. Measurements were made on flat surfaces of otherwise complex parts.

The following provides a brief description of the measurement areas that were collected on Groups 2–5, 7, and 8, respectively:

- Group 2 Suspension (6 DFT): The leaf springs of the FMTV have unique geometries that are difficult, if not impossible, to repaint in the field entirely.

The rear passenger leaf spring was chosen as an easily accessible and consistent part, with DFT measurement taken on the top surface.

- Group 3 Lights and Signals (8 DFT): The lights and signals are a commonly corroded part that is recessed in the bumper of the FMTV, which does not typically become exposed to abrasion or other mechanical coating damage.
- Group 4 Body Panel (Driver Side and Passenger Side) (9 DFT/each): The body panels are large, consistent surfaces that are easy to perform DFT and holiday measurements on and are usually not excessively exposed to mechanical damage.
- Group 4 Cargo Bed (Driver Side/Rear) (7 DFT): The areas of the cargo bed that are not common wear areas offer another commonly found surface that is not usually exposed to mechanical damage. On FMTVs, the section of the cargo bed that was measured was the exterior, driver-side “frame” of the cargo bed upon which the drop-sides attach. The geometry of this part may vary depending on the variation of FMTV being measured.
- Group 4 Body Panel (Rear) (9 DFT): Although the bracket that acts as a high bumper is more likely to be exposed to mechanical damage than the sections of the cargo bed that were measured, it is not a direct wear surface in typical situations and is elevated high enough to avoid chipping from stones being kicked up on the roads, and it offers a flat surface upon which to perform DFT measurements.
- Group 5 Roof (Top) (12 DFT): The roof is a large, flat surface consistent on all vehicles that are also exposed to precipitation that does not interact often with either personnel or with debris on the road.
- Group 5 Hatch (Top) (9 DFT): The hatch is like the roof but more easily removable, and, as such, a separate part was added to distinguish the two areas.
- Group 7 Stowage Box (Driver Side and Passenger Side) (8 DFT/each): The stowage box acts as a large, flat surface suitable for taking measurements on that is common on most vehicle platforms.
- Group 8 Welds (Front/Top) (NA): Welds are a common location for corrosion to occur, although the uneven surface does not allow for DFT to be performed. However, the welds can be measured via holiday testing for the onset of coating failure.

Holiday tests were performed along the edge or along the general surfaces of the 11 above-referenced parts. Ratings were established as the number of “beep” or audible indicators of a holiday in the measurement area. Data were reduced as the holiday density per area or per length of edge.

For each part inspected, the relative area of each SoC (SoC1–SoC4) was noted as an estimate of the total area. Parts could exhibit any of the SoC either singly or in combination. For the present inspection, only SoC1, SoC2, and SoC3 were noted. Percentage areas recorded were estimates of the exact area; the inspection did not default to a minimum area of 5% as was the case with the broader inspection of fielded assets. An arbitrary "corrosion score" was calculated from these data to build a relationship to other factors. The score was (SoC1% + 10) × (SoC2% + 100) × SoC3%.

Twenty-four additional parts were visually inspected (Table 8) for signs of "wear" as indicators on the relative use of the assets. Wear indicators include scratches or erosion on coatings, such as on steps, flooring, drivetrain, and others. This was a subjective indicator, and for these assets, the results correlated with age.

Table 8. Part assemblies inspected as asset use indicators on FMTVs.

Wheels and Lugs	Door Frame
Connection Points	Spare Tire Mount
Brackets	Dashboard
Fasteners	Hydraulic and Air Systems
Drivetrain	Pedals
Bumper	Seats
Steps	Latches
Hydraulic, Air Lines, Connections	Electrical Connectors, Components
Mirrors	Ladder
Hinges	Handles
Frame	Exhaust
Flooring	Turret Ring

4. Data Analysis Results and Model

4.1 Data from Predictions of ARL Data for Coating Breakdown

The present modeling effort focuses on coating breakdown on carbon steel alloy parts. These are the parts that will show visible "red rust" as observed during the inspections. Mitigating such visible corrosion is a major driver for maintenance painting and corrosion mitigation on ground systems.

4.1.1 Incubation Time

Table 9 summarizes the Weibull parameters for the incubation time (time to the first "sign" of surface corrosion) of several coating systems based on the ARL exposure data at CCSFS. The key column is the "scale." Higher scale values represent longer incubation times. The data show a mix from 17 to 70 months—a significant variation. The testing on the zinc-rich–primed panels only extended through 48 months, at which time no degradation was reported; the incubation time is beyond 48 months.

Table 9. Incubation times as defined by Weibull distribution for systems over steel.

Surface profile	Pretreatment	Primer[6]	Topcoat[8]	Shape	Scale (months)
Abrasive blasted	None	MIL-DTL-53022	MIL-DTL-53039	2.2	17.1
Mill finish	Zinc phosphate (chrome seal)	MIL-DTL-53022	MIL-DTL-53039	9.9	53.7
Abrasive blasted	Zinc phosphate (chrome seal)	MIL-DTL-53022	MIL-DTL-53039	10.1	70.8
Mill finish	Zinc phosphate (nonchrome seal)	MIL-DTL-53022	MIL-DTL-53039	2.9	51.9
Abrasive blasted	Zinc phosphate (nonchrome seal)	MIL-DTL-53022	MIL-DTL-53039	3.7	62.7
Mill finish	Silane pretreatment	MIL-DTL-53022	MIL-DTL-53039	2.7	45.9
Abrasive blasted	Silane pretreatment	MIL-DTL-53022	MIL-DTL-53039	1.1	26.6
Mill finish	Trivalent chromium	MIL-DTL-53022	MIL-DTL-53039	8.4	36.2
Abrasive blasted	Trivalent chromium	MIL-DTL-53022	MIL-DTL-53039	2.0	18.8
Mill finish	Zinc-rich primer	MIL-DTL-53022	MIL-DTL-53039		48+[a]

[a] There were no observations of through-film corrosion with a zinc-rich primer after 48 months of exposure.

Figure 10 shows the actual Weibull distributions for three systems over abrasive blasted steel and the MIL-DTL-53022[6]/MIL-DTL-53039[8] coatings. The variations are in the pretreatment and the resultant parameters. The controls are the panels without any pretreatment or "None" (shape, 2.2; scale, 17.1 months), the zinc phosphate with chrome seal (shape, 9.9; scale, 53.7 months), and the zinc phosphate with a nonchrome seal (shape, 3.7; scale, 62.7 months). In general, a lower value of the shape parameter provides for a wider distribution of the data and a higher-scale parameter increases the incubation time. For products such as the zinc phosphate pretreatment (nonchrome rinse), there is a substantial variation in projected incubation for the bottom 10% to the top 10%—34 to 80 months, nominally. This variance is due to multiple nonchrome seals being tested for use as alternatives for chrome seals.

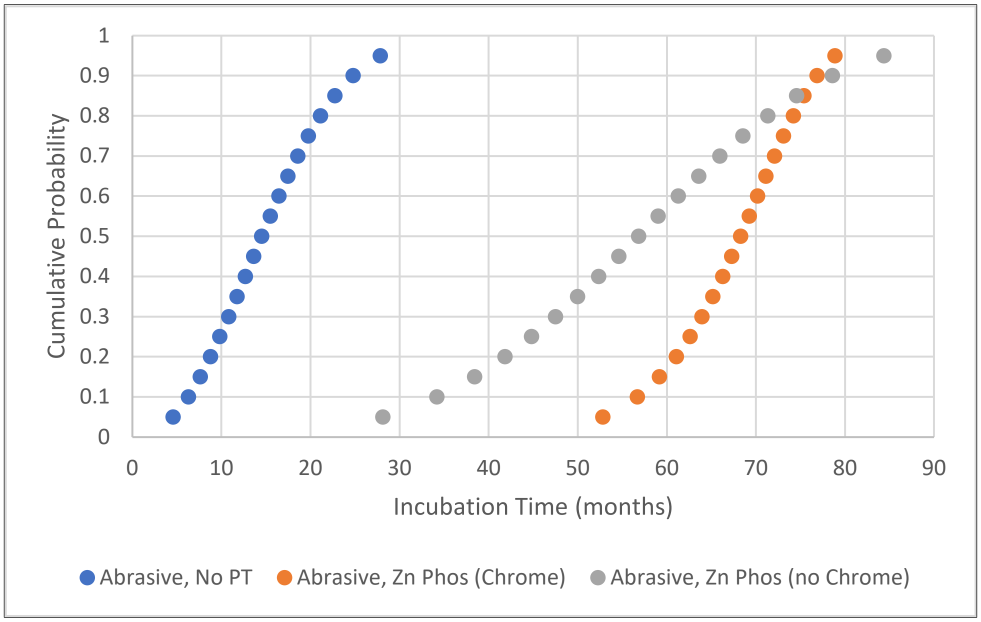


Figure 10. Weibull distribution of incubation time for abrasive blasted steel and MIL-DTL-53022[6]/MIL-DTL-53039[8] coating with three different pretreatments (PTs): no PT (control), zinc (Zn) phosphate (Phos) with chrome rinse, and Zn Phos with a nonchrome rinse.

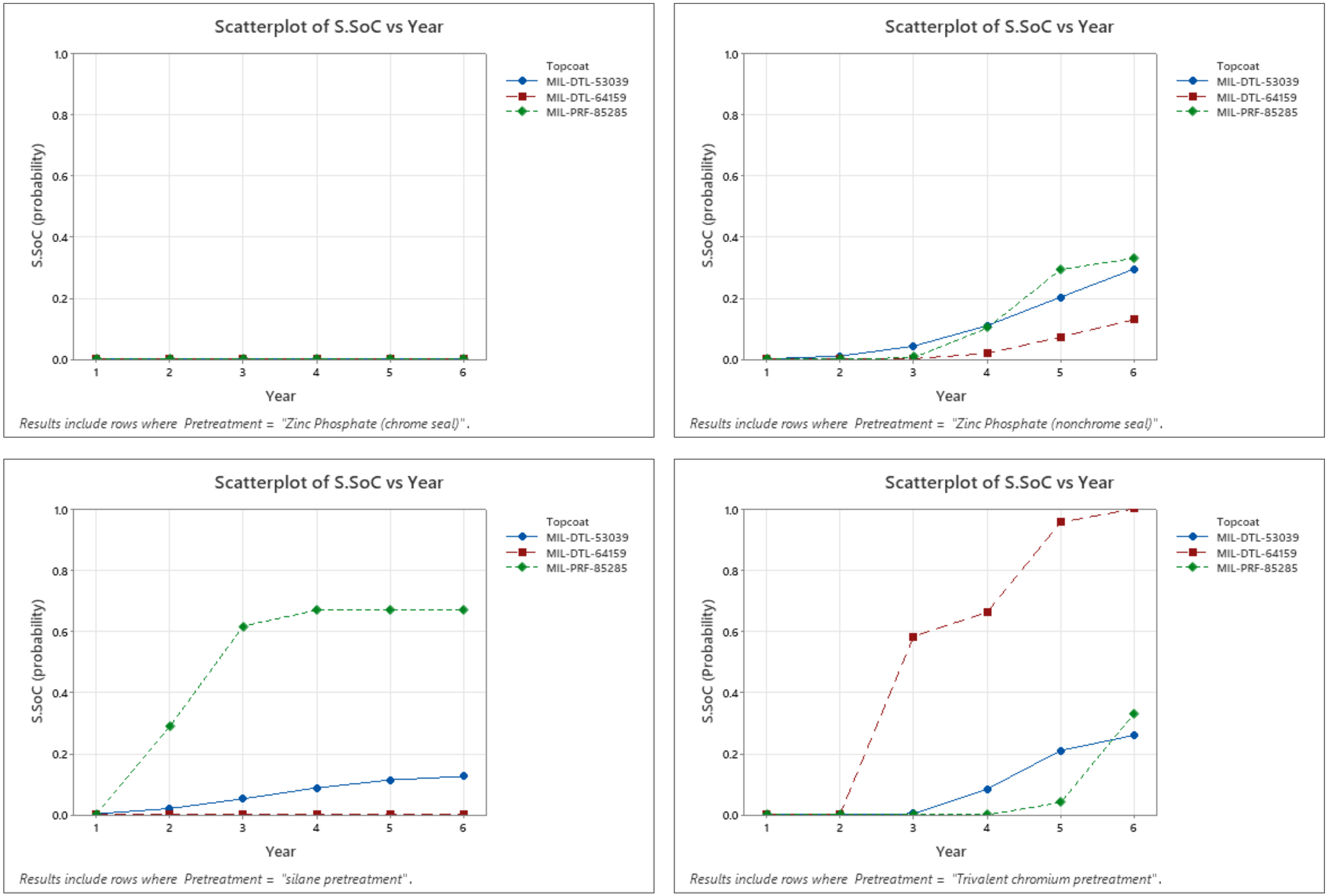
The scale parameter increases with any pretreatments compared with applying the coatings directly to steel, indicating the significance of pretreatment in this coating system.

4.1.2 Through-Film Corrosion

Given the incubation times and the rate of degradation (postincubation) for each combination of surface profile, pretreatment, and primer/topcoat, the probability distribution of each SoC was determined for years 1–6. Appendix C, Tables C-1 through C-3 summarize the probability distributions for through-film corrosion of the MIL-DTL-53022[6]/MIL-DTL-53039,[8] MIL-DTL-53022[6]/MIL-DTL-64159,[9] and MIL-PRF-23377[7]/MIL-PRF-85285[10] systems, respectively. These are derived directly from the tables and procedures shown in Appendix A and discussed above. Figures 11 and 12 provide plots of the expected probability of observing a severe SoC (S.SoC).

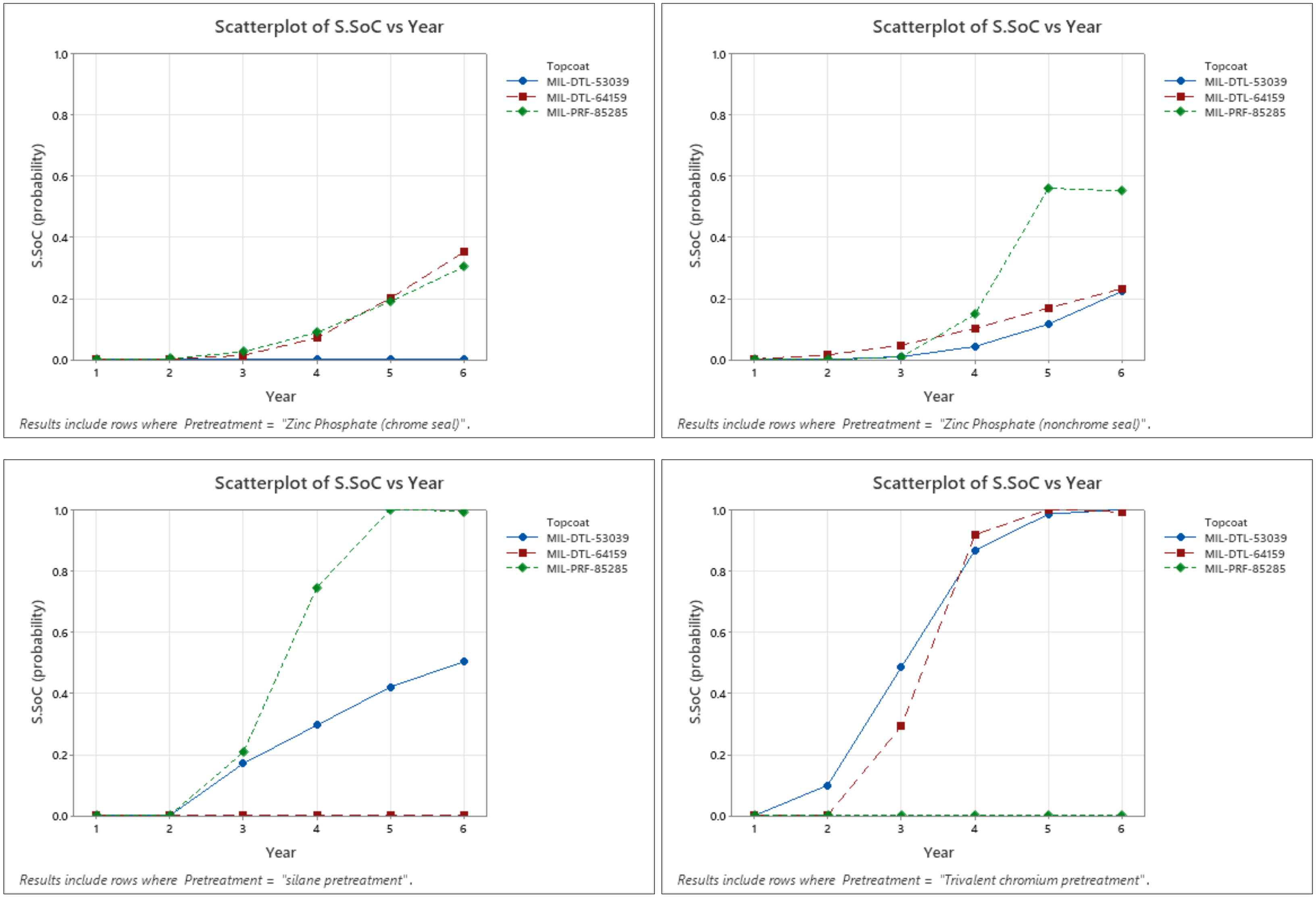
$$S.SoC = SoC2 + SoC3 + SoC4 \quad (3)$$

The plots are segregated by the pretreatment and show the results for each coating system. There are clear effects of time, with increasingly significant corrosion over the 1- to 6-year period, and an evident influence of the pretreatment.



Note: Primer is MIL-DTL-53022[6] for the MIL-DTL-53039[8] and MIL-DTL-64159[9] topcoats and MIL-PRF-23377[7] for the MIL-PRF-85285[10] topcoat.

Figure 11. Probability of S.SoC via through-film vs. time: steel panels over mill finish.



Note: Primer is MIL-DTL-53022[6] for the MIL-DTL-53039[8] and MIL-DTL-64159[9] topcoats and MIL-PRF-23377[7] for the MIL-PRF-85285[10] topcoat.

Figure 12. Probability of S.SoC via through-film vs. time: steel panels over abrasive blasted steel.

Figure 13 shows the main effects plot of the parameters at 6 years of exposure.

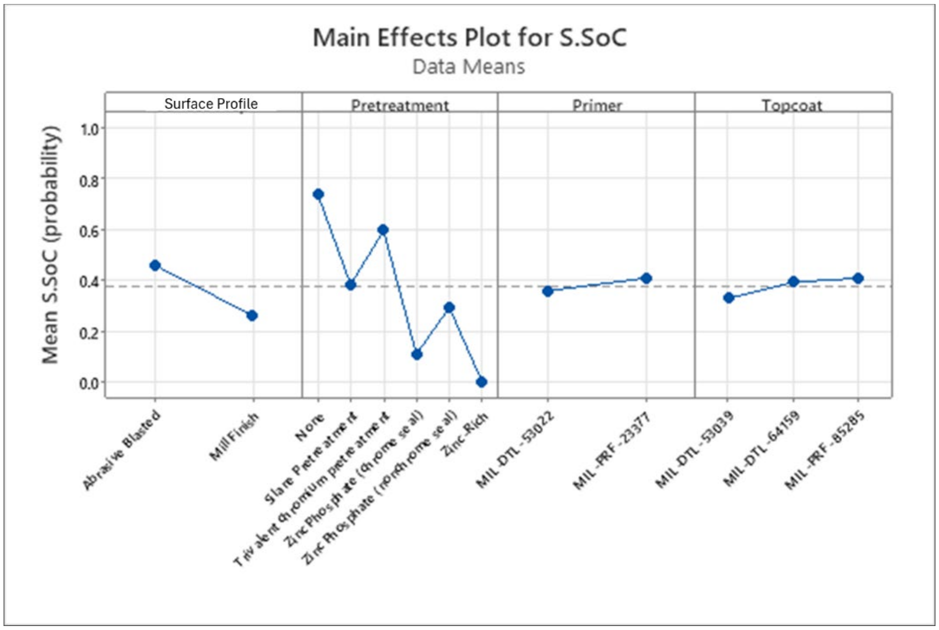


Figure 13. Main effects plot for probability of S.SoC after 6 years, through-film corrosion.

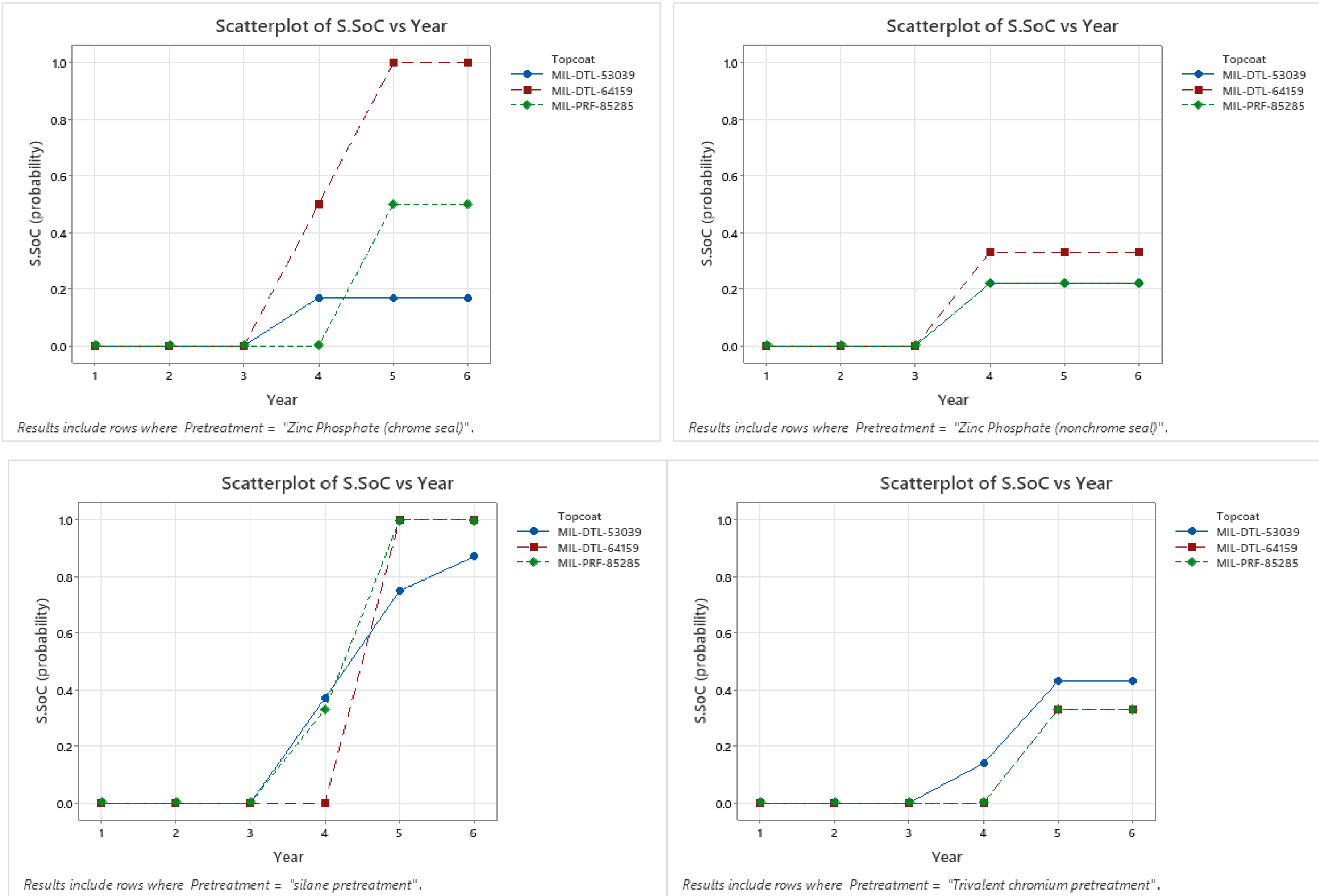
In Figure 13, the y-axis represents the probability of an S.SoC occurring on the coated surface after 6 years. The mean value of 0.38 (38%) is the dashed line. The main effects plot suggests that pretreatment is the major factor influencing projected corrosion. Coatings were observed to perform better over mill finish than over abrasive blasted substrates. (This may relate to the use of an inadequate film of coating, primer, and/or topcoat over an abrasive blasted surface wherein the paint does not adequately cover the “peaks” of the blast profile. Data concerning surface profile roughness measurements and coating film thickness were not available.) The selection of primer or topcoat had no significant impact. The impact of the zinc-rich primer or zinc phosphate pretreatment versus alternative inorganic pretreatments such as silane or trivalent chromium is significant.

A review of Figures 11 and 12 shows that one of the three primer/topcoat combinations appears to be the best or worst performer in each example, leading to the conclusion that none of the primer/topcoat choices is significant concerning longer-term corrosion control. Such inconsistency in the data raises additional questions about the root cause of such variance in the experiments themselves. (The aforementioned Everything Else in Figure 3.)

This empirically derived data demonstrate the need for any pretreatment; eliminating the pretreatment substantially reduces performance. The data show that although the zinc phosphate with nonchrome sealer displays improved performance over a coating system with no pretreatment, it does not necessarily outperform the use of a chrome sealer with zinc phosphate. This does not preclude the use of a nonchrome seal for zinc phosphate (or elimination of all pretreatments) but informs the researcher that there is a higher risk/likelihood of corrosion (earlier onset or higher SoC) that may require more frequent maintenance, but at a lower health/environmental exposure risk, depending on the nonchrome sealer selected.

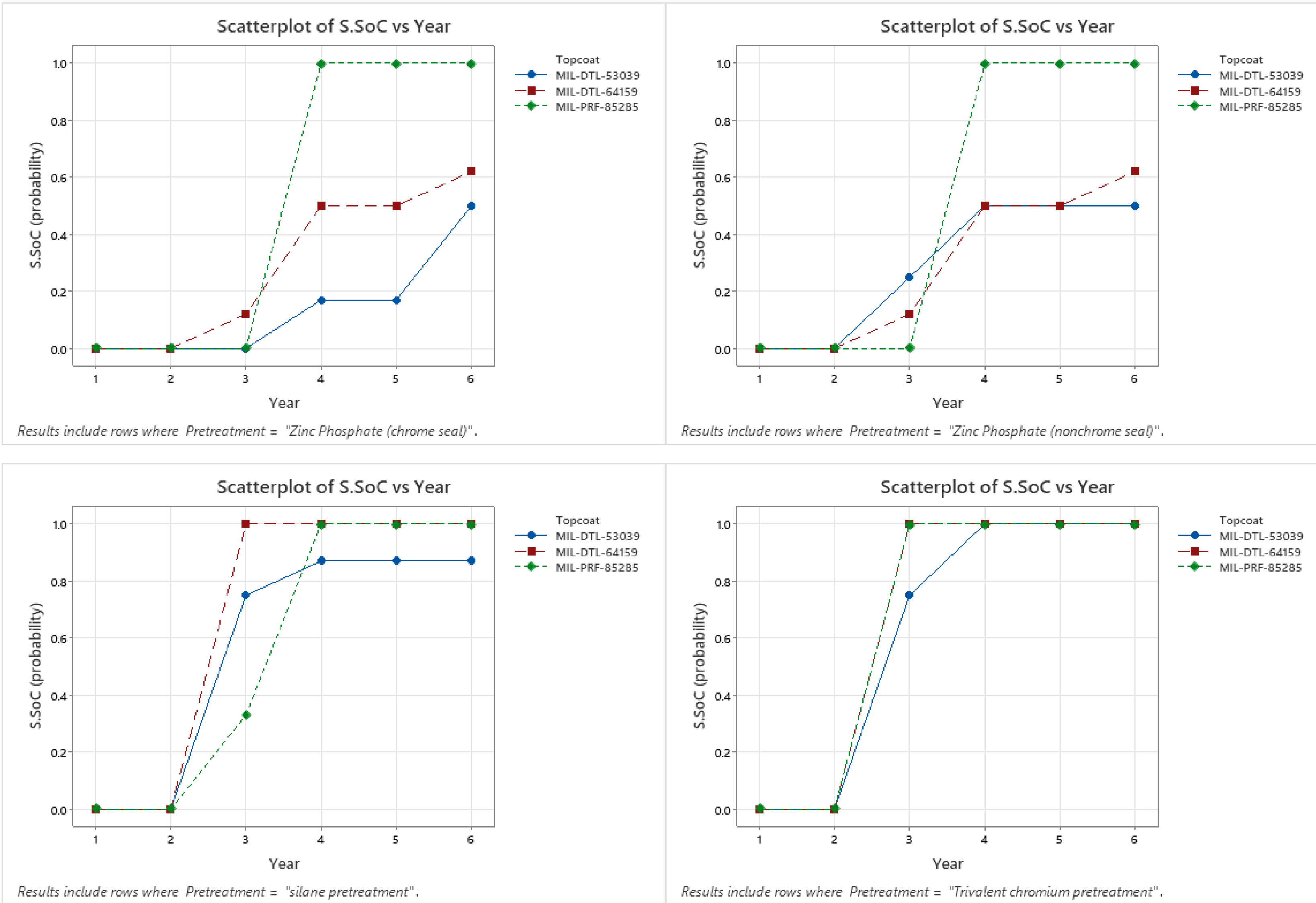
4.1.3 Corrosion Degradation at Scribe Defects

Appendix C, Tables C-4 to C-6 summarize the probability distribution of the SoC associated with the scribe (intentional defect) on test panels for the MIL-DTL-53022[6]/MIL-DTL-53039,[8] MIL-DTL-53022[6]/MIL-DTL-64159,[9] and MIL-PRF-23377[7]/MIL-PRF-85285[10] systems, respectively, at a local corrosion rate of 2.3 mils/year. Figures 14 and 15 show the probability of a S.SoC occurring via creep at a coating defect. The plots are segregated by pretreatment and show results for each coating system.



Note: Primer is MIL-DTL-53022[6] for the MIL-DTL-53039[8] and MIL-DTL-64159[9] topcoats and MIL-PRF-23377[7] for the MIL-PRF-85285[10] topcoat.

Figure 14. Probability of S.SoC via defect creep vs. time: steel panels over mill finish.



Note: Primer is MIL-DTL-53022[6] for the MIL-DTL-53039[8] and MIL-DTL-64159[9] topcoats and MIL-PRF-23377[7] for the MIL-PRF-85285[10] topcoat.

Figure 15. Probability of S.SoC via defect creep vs. time: steel panels over abrasive blasted steel.

Figure 16 shows the main effects on the S.SoC probability via creep at a coating defect.

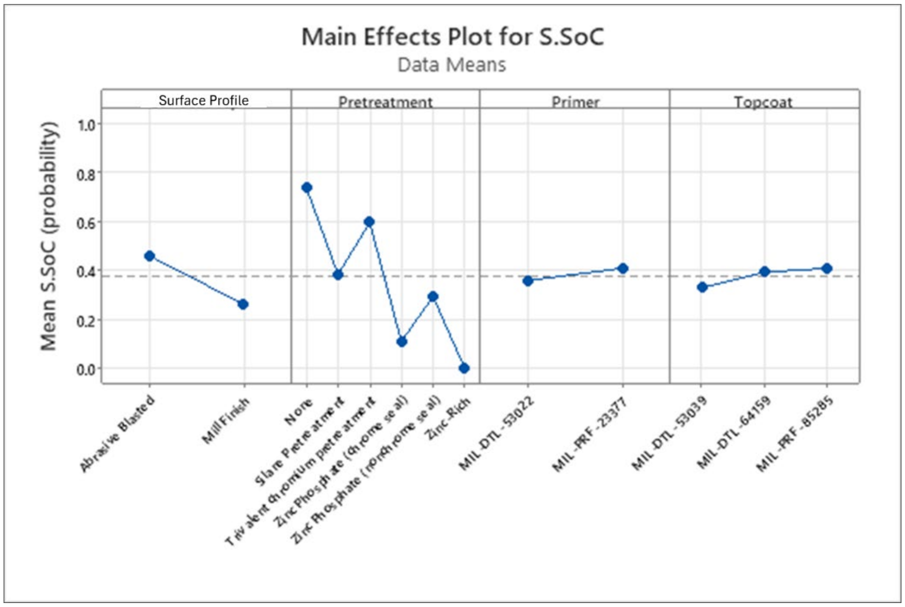


Figure 16. Main effects plot: probability of S.SoC after 6 years and corrosion via creep.

Considering the results of these analyses:

- Surface corrosion and the rate of corrosion on coatings with a scribe are both more severe and rapid than coatings with a fully intact film, as might be expected.
- The pretreatment selection is the primary factor consistently impacting the performance of the CARC as evaluated. For creep corrosion, the zinc phosphate with the nonchrome rinse outperformed the zinc phosphate with the chrome rinse.
- The coatings over the abrasive blasted surface tended to reduce creepage versus the same systems over the mill finished surface.

This data also shows the benefit of using a pretreatment versus the no pretreatment scenario. However, the zinc phosphate with nonchrome seal does have improved performance versus the chrome rinse, although not at a level that may be considered statistically significant. However, in consideration of worker and environmental exposure, even if performance is statistically indistinguishable, the nonchrome seal may have a better "business case" if health and environmental considerations are the primary driving factors (i.e., performance would be no worse than the chrome seal option and significantly improved over using no pretreatment).

4.2 Army Asset Inspections

Consistent with the program objective of optimizing painting processes and maintenance cycles to reduce averse environmental and worker health exposures, the Army asset database analysis aimed to identify the corrosion factors that led to specific maintenance recommendations (i.e., CIC, Spot Paint/CIC, and Repaint). Specifically, in this analysis, we sought to find the relationship between the maintenance recommendation and the form of coating deterioration and corrosion.

For the assets identified, the inspection process identified up to 110-part assemblies (a.k.a. parts) with corrosion. Initially, the analysis summed the magnitude of each form of surface corrosion (all SoC) on the parts and compared this value with the recommended maintenance. Table 10 summarizes this data. The data show that (nominally) 7%–11% of the area of a part was recorded as corroding, with a small increase moving from the lowest level of maintenance (CIC) to the highest (Repaint). The distributions overlap with each other with a large standard deviation (StdDev), suggesting that the total corroding area of a part is not significant in determining the maintenance recommendation. This analysis is limited by the minimum value of 5% assigned to each SoC rating. The dataset does not distinguish small areas (<0.1%) of SoC1 that might exist on CIC-only assets. Furthermore, the percentage areas of corrosion on these part assemblies are well below the common 25% value assigned to categorize items for repainting.

Table 10. Average SoC area on parts segregated by maintenance classification.

Maintenance classification	Avg. corroding area parts inspected (%)	StdDev
CIC	7.2	9.5
CIC/Spot Paint	8.8	9.0
Repaint	10.9	11.6

Subsequently, in this analysis, only those parts with S.SoC defined herein as parts with ratings of SoC2, SoC3, or SoC4 were considered. In doing so, the ubiquitous presence of initial corrosion (i.e., SoC1) was eliminated. Table 11 shows this result. Although overlap remains, the mean areas increase (nominally) from 1% to 2% to 5% of the surface affected by S.SoC from the lowest level of maintenance (CIC) to the highest (Repaint). Although the values are still affected by the minimum 5% rating, the data suggests that the recommended maintenance is closely aligned with more significant corrosion versus any corrosion.

Table 11. Average S.SoC area on parts segregated by maintenance classification.

Maintenance classification	Avg. corroding area parts inspected (%)	StdDev
CIC	1.0	4.6
CIC/Spot Paint	2.2	5.2
Repaint	4.6	8.2

The maintenance classification was then examined by the total part count per asset with an S.SoC indication. This eliminated any distinction between the magnitude of the surface area of an assembly with a particular S.SoC. The examination included a distinction of those assets that showed zero parts with a S.SoC that were also placed in one of the three maintenance classifications. Table 12 shows the distribution of the maintenance classifications for the assets. Approximately 22% of the assets showed no parts with a S.SoC, and 78% had one or more indications of a part with an S.SoC.

Table 12. Percentage of assemblies per maintenance classification.

Maintenance classification	Percentage of assemblies	
	Assets with "0" indicated parts with an S.SoC (%)	Assets with >0 indicated parts with an S.SoC (%)
CIC	15.9	3.9
CIC/Spot Paint	80.6	77.9
Repaint	3.5	18.2

The data nominally show the same percentage of the population with a CIC/Spot Paint recommendation. However, there is a reversal in the percentages of assets with either a CIC or Repaint classification. This further suggests the importance of the part assembly count with severe corrosion.

Figure 17 shows the distribution of the S.SoC assembly counts per maintenance classification. There is some variation in the distributions for each maintenance classification based on assembly counts.

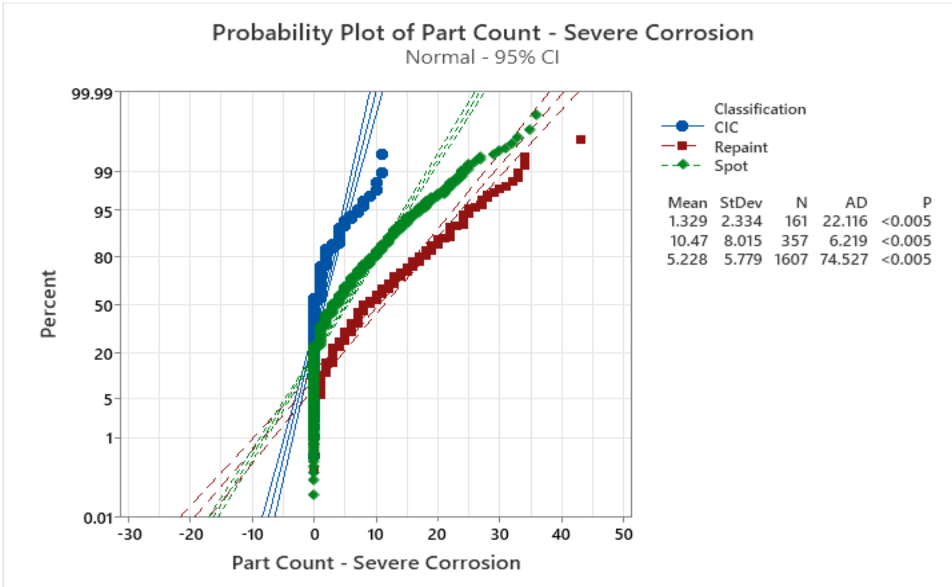


Figure 17. Normal distribution of part count with S.SoC per maintenance classification.

Provided with the significance of S.SoC versus any corrosion, the dataset was reviewed to identify those parts most often showing some S.SoC. Table 13 summarizes the key parts into 8 groups of 4, totaling 32 parts. In general, the groups reflect the relative ranking of the part in terms of the frequency of severe corrosion. In some cases, the parts have been moved to an adjacent group based on common location (e.g., the underbody).

Table 13. Percentage of assets showing an S.SoC for one or more key part assemblies.

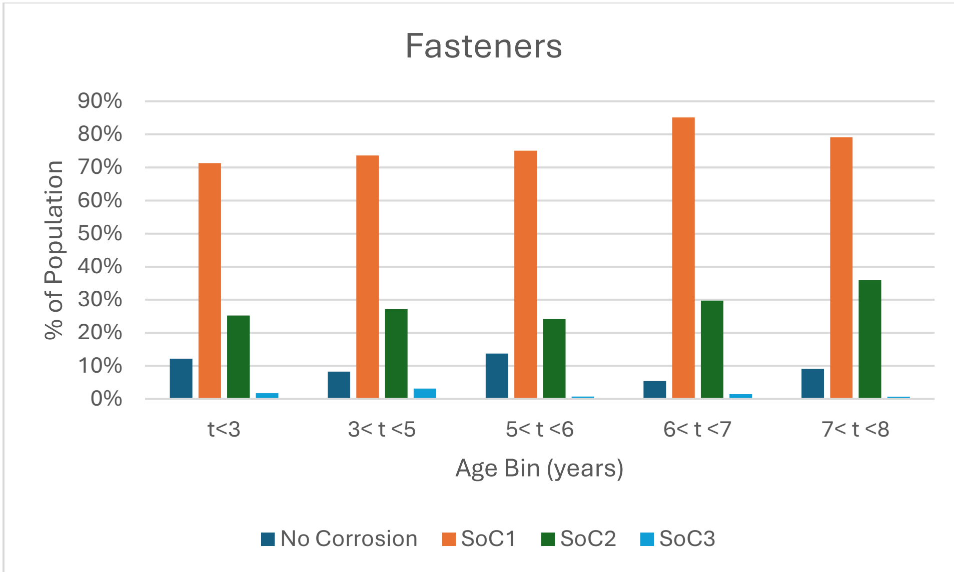
Group1		Group5	
WHEELS AND LUGS	47%	DOOR FRAME	3%
CONNECTION POINTS	52%	SPARE TIRE MOUNT	3%
BRACKETS	32%	ROOF	3%
FASTENERS	28%	HYDRAULIC AND AIR SYSTEMS	5%
Group2		**Group6**	
SUSPENSION	29%	PEDALS	3%
DRIVETRAIN	28%	DASHBOARD	2%
BUMPER	22%	SEATS	7%
STEPS	13%	LATCHES	5%
Group3		**Group7**	
HYDRAULIC AND AIR LINES AND CONNECTIONS	17%	STOWAGE BOXES	4%
MIRRORS	12%	LADDER	6%
LIGHTS AND SIGNALS	17%	ELECTRICAL CONNECTORS AND COMPONENTS	3%
HINGES	3%	HANDLES	6%
Group4		**Group8**	
BODY PANELS	8%	TRUCK BED	2%
CARGO BED	9%	EXHAUST	5%
FLOORING	5%	TURRET RING	3%
FRAME	6%	WELDS	2%

4.2.1 Age Impacts

Age was the initial factor investigated for its impact on corrosion. For this effort, the SoC ratings of parts up to an age of 8 years were investigated. A maximum age of 8 years was considered a period in which an entire asset was unlikely to have received substantial repainting. Investigations of age effects are a logical effort, especially for comparison to coating performance in standardized testing.

Data were divided into five bins, each containing nominally the same data count, so the elapsed time between data became compressed in age regions with a higher population density—6–8 years in this case. Figure 18 shows two samples: fasteners and door frames. The data shows the SoC at each time interval. There are no observations of SoC4.

Fasteners show consistent distributions in part corrosion in each age range. Door frames show some slight growth in reported SoC1 past the first two age bins. All the reports are for SoC2 or less. However, in general, age by itself is not a strong indicator of corrosion. This same finding applied to the 32 key parts.



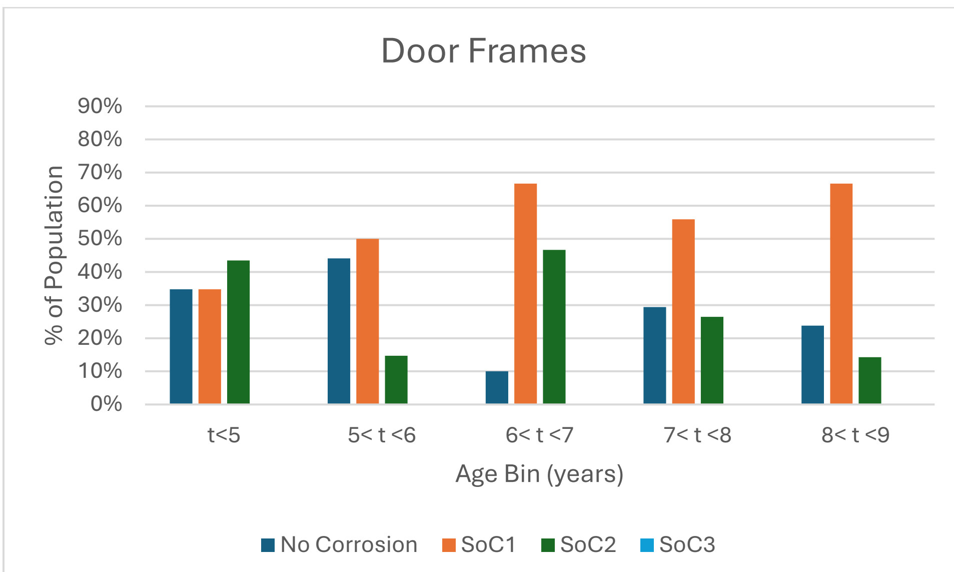


Figure 18. Trends in SoC growth vs. time, fasteners, and door frames.

4.2.2 Coating Delamination

Paint delamination was often noted on the 41,664-part assemblies rated. A total of 22% (8,962) of the parts showed some coating delamination. Only 3% (1,319) showed delamination and an S.SoC; only 9% (3,705) showed delamination and any form of corrosion. This seems to suggest that delamination phenomena are not associated with the corrosion observations, yet it occurs in 22% of the parts. Figure 19 shows a normal distribution plot of these findings segregated by the maintenance classification. Increased delamination appears to differentiate (albeit weakly), compared with the S.SoC count (Figure 19), with the higher levels of recommended maintenance. Figure 20 shows a range of delamination observations, from large areas to smaller areas on components. Some delamination occurs at the substrate and other delamination events are observed at the interface of separate coating layers. Much of the delamination occurs over stainless steel and aluminum substrates, known for their corrosion resistance compared to carbon steels, hence the lack of correlation to corrosion.

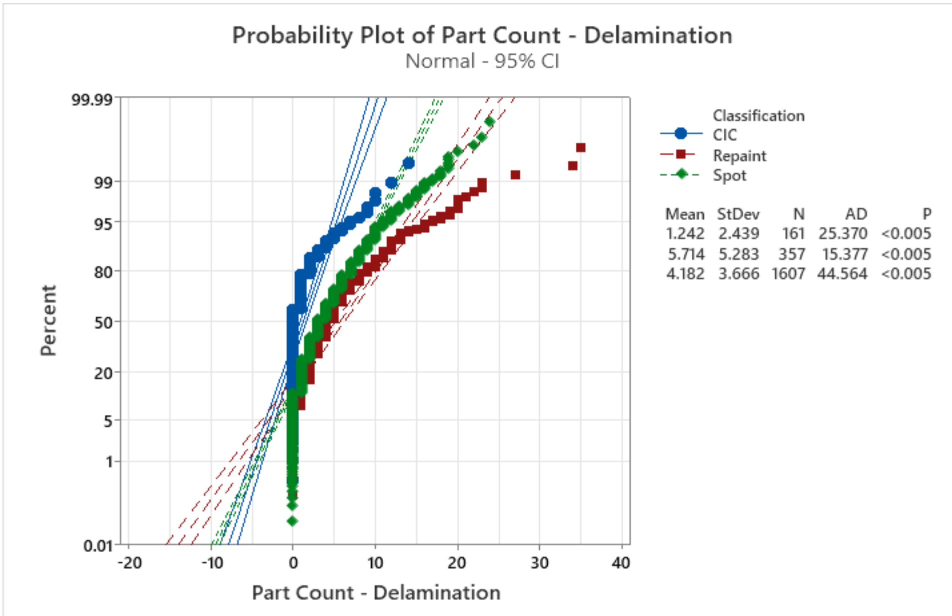


Figure 19. Distribution of part count with delamination per maintenance classification.

Figure 20. Examples of delamination (cargo bed side, hinge, hydraulic line).

4.2.3 Mechanical Damage

As opposed to standard test panels, fasteners and door frames are subject to physical damage in the field and operations. Upon reviewing the dataset for the 2,125 assets, there were 41,664-part assemblies rated. Some form of mechanical damage was noted on 26% (10,866) of the part assemblies. Ten percent (4,252) showed both mechanical damage and an S.SoC. Mechanical damage was often present, and it had a limited correlation (~30%) with the presence of S.SoC. This suggests that S.SoC and mechanical damage are not independent variables. Mechanical damage had less association with specific maintenance classifications than either the S.SoC part count or the delamination count.

4.2.4 Mileage

Unlike the performance of standard test panels, the age of fielded items does not correlate with the corrosion observed. Operational use appears to be more critical based on casual association of corrosion, paint damage, and signs of “wear and tear.” Mileage was investigated as an analog to use, and the associated impacts of abrasion, mechanical impacts, higher temperatures, and other operational incidents that might occur.

The program also identified a subset of assets that are used more frequently than others. DEVCOM Ground Vehicle Systems Center (GVSC) performed a study analyzing (Figure 21) the average miles driven per day for 75 FMTV assets over a 2-year monitoring period. A small fraction (2%–5%) of FMTVs can be driven four times more frequently than the rest of the trucks. The predominant use, or nonuse, at the lower portions of the distribution may explain the relatively smaller proportions of the field observations requiring only CICs and those requiring repainting. Approximately 75% (75.5%) of the fleet shows a need for spot painting versus 7.5% for CIC, only and 17% for repainting.

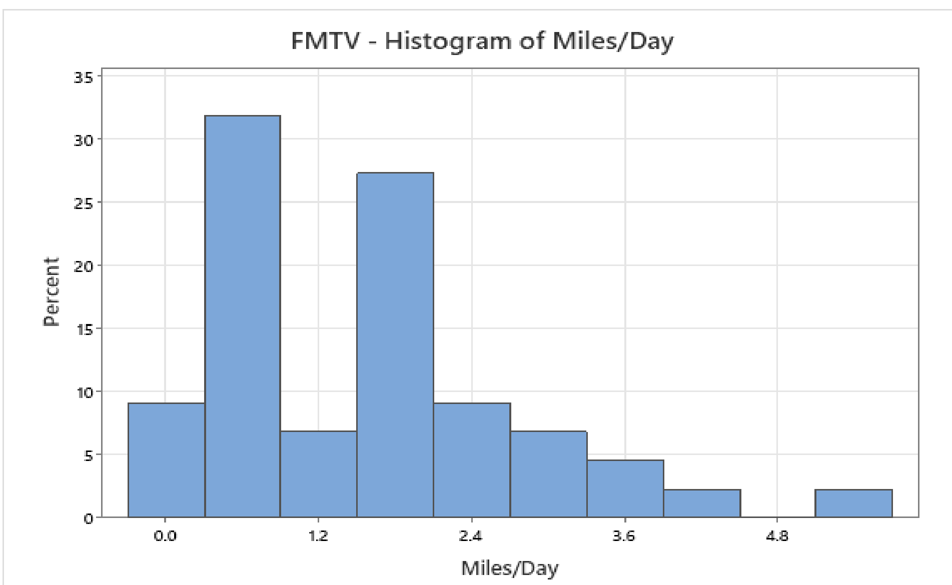


Figure 21. Average miles driven per day, 75 FMTVs.[12]

For an assessment of mileage impacts, there is insufficient data in the database to consider only the FMTV/LMTV families. The FMTV dataset was augmented with data from the largest family, High Mobility Multipurpose Wheeled Vehicle (HMMWV), where surveyors were able to obtain additional mileage readings onsite more easily than the other vehicles surveyed. The set comprises nominally 82% HMMWV part corrosion ratings and 18% FMTV/LMTV part corrosion ratings. For each asset, the mileage was noted along with the part count of S.SoC indications. In all cases, the observations were based on the previous 32 key parts identified. The mileage and part counts were separated into four bins each. Table 14 shows the result of this analysis.

Table 14. Mileage impacts on S.SoC part count.

Total mileage	Observations	Count ≤5 S.SoC (%)	Count >5 and ≤10 S.SoC (%)	Count >10 and ≤15 S.SoC (%)	Count >15 (%)
1,000	472	69	17	9	4
1,000–5,000	1,076	56	22	13	8
5,000–20,000	1,093	52	24	14	10
20,000–60,000	316	50	24	16	10

Increases in mileage lead to higher counts of parts exhibiting S.SoC; increases in the same factor associated with the need for more extensive maintenance.

The above data was also queried to establish the average part counts for each SoC (a.k.a., NoCorr, SoC1, or S.SoC). The data were segregated by the same mileage bins. When the total part count was less than 32 parts, the balances were assumed to show NoCorr. Table 15 shows the results of this analysis.

Table 15. Corrosion rating distribution vs. particular SoC.

Total mileage	NoCorr (%)	SoC1 (%)	S.SoC (%)
1,000	65	21	15
1,000–5,000	61	21	17
5,000–20,000	58	22	20
20,000–60,000	54	23	23

4.2.5 Inspection Location

The data was also assessed based on the location of the inspection. Although it is recognized that Army assets can move among many locations, the present dataset does not have a historical location for each asset. For this analysis, the focus was on FMTV/LMTVs and the target 32 key parts in the observation location. Data were examined from 40 inspection locations. For each location, the average yearly temperature and relative humidity was determined from commercial weather databases for a target year of 2020. These values were used to determine an approximate TOW per year.[13] These data had a normal distribution, and locations were assigned either a low (<2,406 h), mid (2,406–3,403 h), or a high (>3,406 h) TOW, each comprising one-third of the distribution range. In addition, a possible accelerating effect was noted based on the proximity of the location to the ocean; locations less than 5 miles from the ocean were assigned a "Yes" value for salt.* Table 16 summarizes the installations and the resultant characterization.

Table 16. TOW and ocean proximity for fielding locations.

Location	TOW (h)	TOW level	Ocean effects
ARNG SMYRNA, TN	2,963	Mid	No
CAMP CARROLL	2,430	Mid	No
CAMP HUMPHREYS	4,112	High	No
CAMP SHELBY, MS	3,612	High	No
EGLIN AFB, FL	4,502	High	Yes
FT BENNING, GA	2,569	Mid	No
FT BLISS, TX	253	Low	No
FT BRAGG, NC	2,823	Mid	No
FT CAMPBELL, KY	3,081	Mid	No
FT CARSON, CO	666	Low	No
FT DIX, NJ	2,221	Low	No
FT DRUM, NY	3,694	High	No
FT EUSTIS, VA	3,104	Mid	No
FT GORDON, GA	2,559	Mid	No
FT HOOD, TX	2,291	Low	No
FT HUNTER-LIGGETT, CA	2,348	Low	No
FT INDIANTOWN GAP, PA	2,570	Mid	No
FT IRWIN, CA	134	Low	No
FT JACKSON, SC	2,569	Mid	No
FT KNOX, KY	2,596	Mid	No
FT LEONARD WOOD, MO	2,548	Mid	No
FT MCCOY	2,860	Mid	No
FT MCCOY, WI	2,860	Mid	No
FT POLK, LA	3,742	High	No
FT RILEY, KS	2,430	Mid	No
FT SILL, OK	1,856	Low	No
FT STEWART, GA	4,320	High	No
FT STORY, VA	3,269	Mid	Yes
FT WAINWRIGHT, AK	1,287	Low	No
GUAM	5,017	High	Yes
HAWAII	2,787	Mid	Yes
JOINT BASE CHARLESTON, SC	4,100	High	No
JOINT BASE CHARLESTON, SC AFLOAT	4,100	High	Yes
JOINT BASE ELMENDORF RICHARDSON, AK	2,193	Low	Yes
JOINT BASE LEWIS MCCHORD, WA	4,365	High	Yes
MI NG Grayling	2,942	Mid	No
RRAD, TX	3,055	Mid	No
MI NG Lansing	3,279	Mid	No
PUERTO RICO	4,405	High	Yes
SAIPAN	5,647	High	Yes
SCHOFIELD BARRACKS, HI	2,787	Mid	No
YAKIMA TRAINING CENTER, WA	1,862	Low	No

* The impacts of local microclimates are well documented and are not characterized within the inspection dataset; the present analysis attempted a simple generalization of each site based on easily retrieved information.

Table 17 provides a summary of the analysis. As the projected TOW increases, there is a significant increase in the presence of corrosion and more S.SoC. The impact of salt, as characterized, is less clear, although there is a clear difference in moving from a low to a high TOW. The data for the mid TOW is based on only a single site that fell into that category; hence, that data has fewer observations. There are fewer items with NoCorr when considering the proximity to the ocean.

Table 17. Summary of impacts of inspection location TOW and (possible) salt exposure on observed SoC.

	TOW level	NoCorr (%)	SoC1 (%)	S.SoC (%)
No salt	Low	54	31	15
	Mid	41	37	22
	High	33	33	34
Salt effect	Low	50	33	17
	Mid	1	37	62
	High	26	45	29

The impact of the local environment on corrosion of the Army assets is noted. In the model, environmental considerations were achieved by assuming a corrosivity of the site, utilizing corrosion rates of 25, 59, and 100 μm/year, applied to the creep data from the test panels. The higher corrosion rates shift more parts to an S.SoC.

4.2.6 Paint Quality on Army Assets

The analysis of the detailed Fort Dix, New Jersey, data is intended to better support the root causes of any S.SoC observed. Appendix D provides a summary of the physical areas on the FMTVs that were inspected for DFTs and holidays.

Our initial analytical efforts were focused on the recorded paint thickness. The DFT data were averaged and viewed as a log-normal distribution; this eliminated the possibility of DFT projections below 0.0 mils of thickness. For each component inspected, a minimum expected DFT was calculated from the DFT distribution. This was calculated as the thickness corresponding to the bottom 5% of the coated surface (i.e., 5% of the cumulative distribution).

With the assumptions that MIL-DTL-53072[1] was the governing specification and that a MIL-DTL-53022[6] epoxy primer (2.0 ± 0.5 mils DFT) was applied with a MIL-DTL-53039[8] (2.5 ± 0.5 mils DFT) topcoat, the expected DFT would be in the range of 3.5–5.5 mils. The 5% projected DFT was compared with this range, and DFT projections below 3.5 mils were labeled "LOW." Those above 5.5 mils were labeled "HIGH," and those in the range were labeled "SPEC." Appendix D includes a summary of these data per part segregated by any S.SoC.

Table 18 summarizes the distribution of the SoC observations on a part assembly for each predicted DFT range (LOW, SPEC, or HIGH). In general, where a larger proportion of the observations indicate a S.SoC rather than NoCorr (None), a larger part of the population is represented by areas of LOW DFT.

Table 18. Summary observed SoC per inspected part assembly segregated by estimated DFT representing minimum 5% of area.

Part	Observed SoC	LOW DFT (%)	SPEC DFT (%)	HIGH DFT (%)
Body Panel	None	0	52	48
	SoC1	20	60	20
	S.SoC	14	50	36
Cargo Bed	None	0	40	60
	SoC1	0	100	0
	S.SoC	50	50	0
Hatch	None	7	50	43
	SoC1		None	
	S.SoC	50	50	0
Lights and Signals	None		None	
	SoC1	30	70	0
	S.SoC	100	0	0
Roof	None	0	29	71
	SoC1	0	100	0
	S.SoC		None	
Stowage Box	None	15	62	23
	SoC1	0	100	0
	S.SoC	25	75	0
Suspension	None		None	
	SoC1	0	100	0
	S.SoC	7	60	33

Not all assets inspected have a large variation in DFT. Figure 22 shows the variation in the projected 5% DFT for the newest of the FMTV assets evaluated (<1 year old). This is a small variation compared with the other FMTV assets inspected. Figure 23 shows similar data for three FMTVs manufactured in June 2018. For these, the present coating thickness seems more variable.

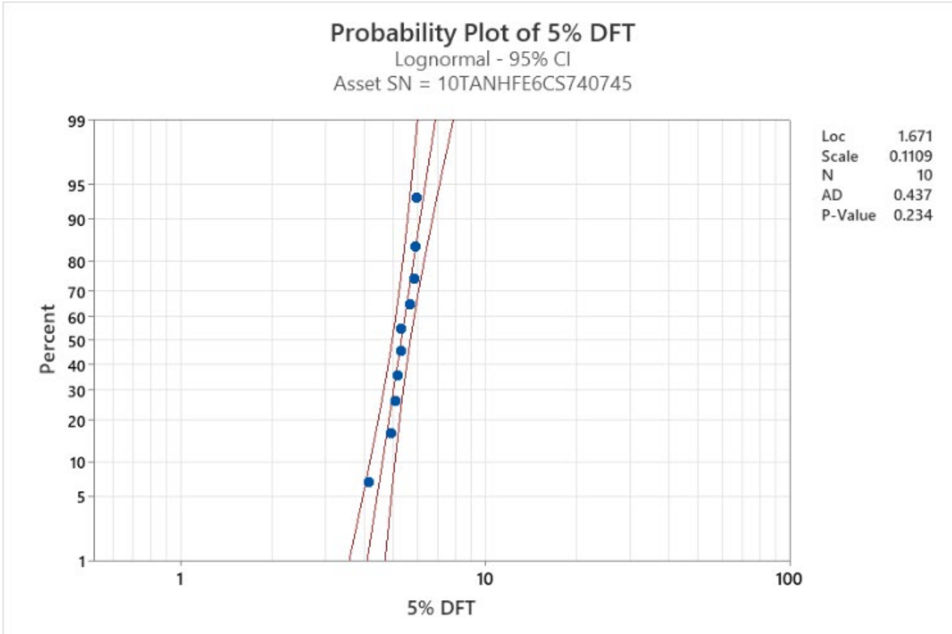


Figure 22. Variation in 5% DFT for all steel parts, FMTV April 2024 DoM.

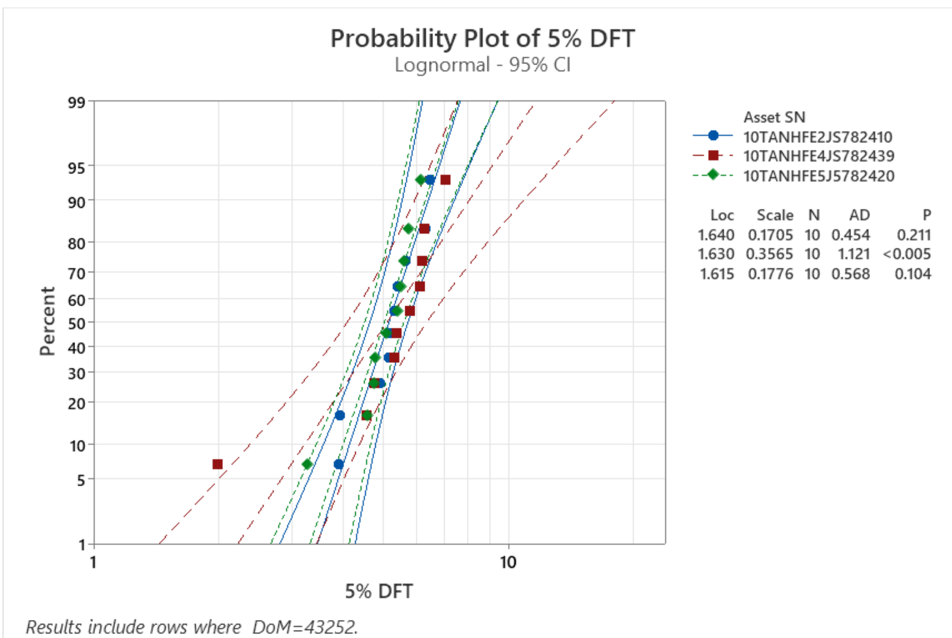


Figure 23. Variation in 5% DFT for all steel parts, FMTV June 2018 DoM.

Figure 24 shows the distribution in body panel 5% DFT across the 16 assets inspected. Unlike the body panels on one specific asset, the variation across multiple assets for a single part can be quite significant.

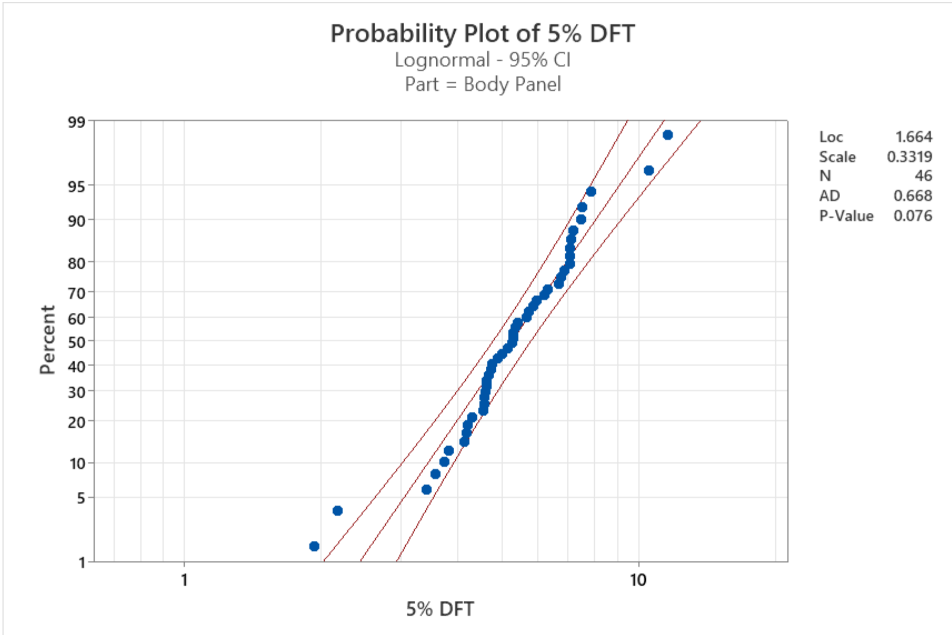


Figure 24. Variation in 5% DFT for body panels observed.

Concerning holidays (i.e., through-film defects), the analysis estimated a holiday density per square foot for testing of "flat" areas on the assets and holidays per linear foot for testing on edges. Where the audible "beep" indications of the holiday detector sounded continuous over a flat area, an estimate of the number of holidays was made by assuming this length to be a square with five holidays per square inch. Therefore a 2- × 2-inch area of continuous holidays was assumed to have (2 × 2 × 5) 20 holidays. Discrete individual holidays were added to this value. For edges with continuous sounding over a given length, five holidays were assumed per inch of continuous sounding. These were added to any discrete holidays.

Tables 19 and 20 summarize the results of the holiday tests. Testing was not possible on the lights and signals due to corrosion or on the edges of the hatches. The data show the suspension systems to be a continuous holiday. Four of 46 body panels had a "substantial" number of holidays in the coating. These findings skewed the overall data toward high averages. Nine of 22 stowage boxes showed a measurable number of holidays. Few were detected on the cargo bed, hatch, or roof. Edges were found to have a substantial number of holidays with at least one per inch.

Table 19. Holiday density (no./ft^2) per part on flat surface.

Variable	Part	Mean	StdDev	Minimum	Maximum
Holidays (no./ft^2)	Body Panel	11.7	43.2	0	216.0
	Cargo Bed	0.2	0.3	0	0.6
	Hatch	0.2	0.3	0	1.2
	Roof	0.2	0.6	0	2.1
	Stowage Box	3.3	7.1	0	30.9
	Suspension	440.2	569.7	0	1152.0

Table 20. Holiday density (no./ft) per part on edges.

Variable	Part	Mean	StdDev	Minimum	Maximum
Holidays (no./ft of edge)	Body Panel	1.8	8.9	0	60.0
	Cargo Bed	7.3	18.6	0	60.0
	Hatch	. . .	. . .	. . .	. . .
	Roof	1.4	4.1	0	16.2
	Stowage Box	2.3	4.2	0	13.3
	Suspension	19.5	28.3	0	60.0

This testing occurred on assets after variable times in the field. For obvious reasons, holiday tests could not be run in areas that were already corroded, so corroded areas are excluded from the above measurements. The holidays detected were not corroding even after 10+ years' service, so there seems likely to be a threshold of holidays that can be determined with a detector that will not suffer from corrosion. It is conceivable that the larger holidays corroded much earlier in the coating life. The findings may still indicate a propensity for weak points in the coatings as originally applied.

Figure 25 shows the effect of three variables on the mean area of parts affected by S.SoC. Recall that, unlike the large field dataset used for most of this analysis, the Fort Dix inspectors noted the extent of an area affected by a SoC in 0.5% increments versus the 5% increment of the larger database. The data suggest that age per se is not a great predictor. Use, as evidenced by marring and wear not associated with corrosion, is a strong contributor to corrosion. Coating film thickness control is also important.

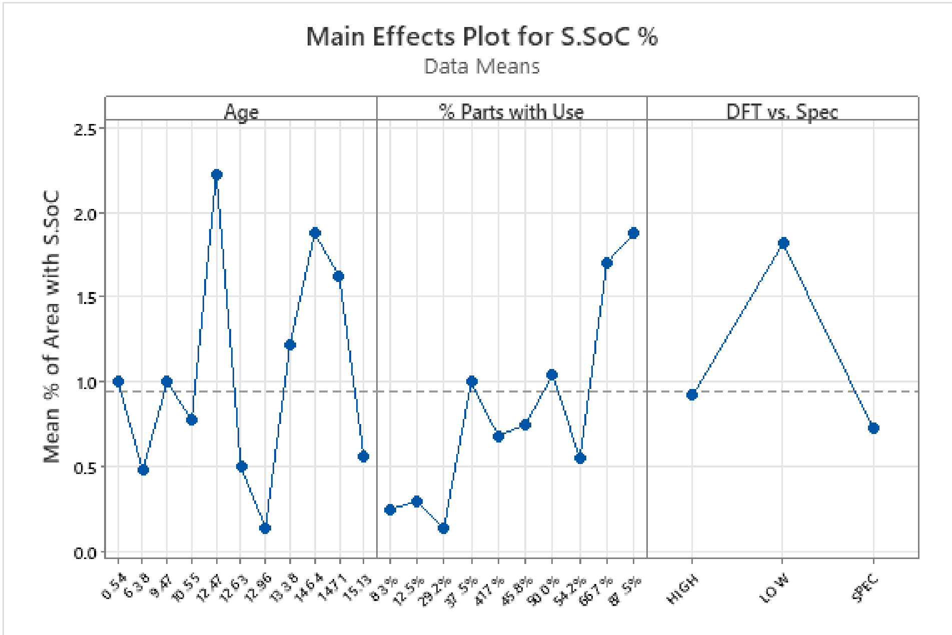


Figure 25. Main effects plot regarding FMTV age, percentage of parts with use, and paint DFT vs. specification on mean area with S.SoC.

The data from the Fort Dix inspection also helped provide an estimate of the effect of "poor quality" coating, as evidenced by DFT control, on the subsequent corrosion. This factor is derived from a more detailed assessment of body panels and lights and signals. The body panels represent (likely) the easiest part to paint evenly on the FMTV; the lights and signals have the greatest variation.

The data from the Fort Dix inspection provided the proportionality of NoCorr (None), SoC1, and S.SoC for a range of the estimated DFT representing the lower 5% of the DFT population (LOW, SPEC, HIGH). A CPT that relates the actual observed SoC based on the DFT distribution was derived from multiple linear regression of the data. The analysis assumed that panels could not "self-heal," (meaning the corrosion only gets worse with time), so an SoC1 initial state could not be a precursor to "NoCorr" and S.SoC initial state could not become SoC1 or NoCorr. Constant values of 1 were assigned to the expected corrosion when the coating DFT was in the specified range. This allowed the linear regression to calculate only 3–4 constants per assembly classification as opposed to 27, allowing for some estimate with only 24 examples of body panels and 16 for lights and signals. However, there remains scatter in the best-fit analysis. The values derived for the two assemblies of parts were averaged and used in the model. The impact of a variation in DFT on corrosion began with an assumption that a specification coating would result in an expected distribution of 60% NoCorr, 20% SoC1, and 20% S.SoC. This is nominally the summary of the data from the Fort Dix inspection for coatings at the SPEC thickness for all part assemblies less than 10 years old. Table 21 summarizes the conditional probabilities.

Table 21. CPT for impact of coating quality on actual observation of SoC.

Impact of DFT control on predicted SoC				
Input 1	**Input 2**	**None**	**SoC1**	**S.SoC**
None	LOW	0.265	0.64	0.095
None	SPEC	1	0	0
None	HIGH	1	0	0
SoC1	LOW	0	0.4	0.6
SoC1	SPEC	0	1	0
SoC1	HIGH	0.93	0.07	0
S.SoC	LOW	0	0	1
S.SoC	SPEC	0	0	1
S.SoC	HIGH	0.665	0.145	0.195

Appendix E includes a summary of other trials on the impact of coating film thickness and holiday proximity on coating deterioration. The data includes steel panels treated with a common military specification E-coat primer and a CARC topcoat system. The data suggests that low film thicknesses will increase coating creep. The testing also suggests that holidays near each other will result in more rapid creep around each holiday. Both DFT and holiday density can be important to coating performance.

4.3 Model Outputs

The previous sections presented data from two related, but diverse, sources as illustrated in Figure 26.

1) Panel test data that gives the "Standard Performance" of a variety of applied coating systems composed of the surface profile, pretreatment, primer, and topcoat applied on different substrate materials.
2) "Real-world" field observations of corrosion occurring on FMTV/LMTV assemblies of parts primarily made up of items with steel substrates and a fixed applied coating system. These assemblies are a mixture of parts, sometimes with dissimilar materials (some of which may have been plated). The assemblies contain complex, difficult-to-coat geometry, and the quality control of the coating application can vary. They have been subjected to severe environments and use that is not replicated in the coupon panel testing.

By combining these two data domains, we get an opportunity to extend predictions of standard coating performance in controlled laboratory testing to the expected field performance experience in the real world. This results in our ability to anticipate the corrosion severity condition of various parts on the vehicle and thereby forecast the future need for maintenance actions (e.g., CIC, Spot Paint, Repaint, and part replacement).

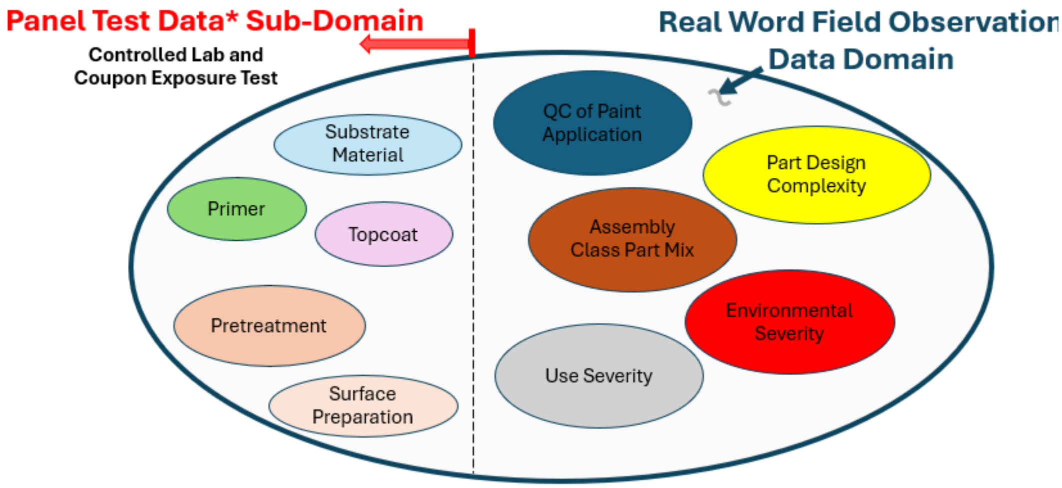


Figure 26. Real-world coating performance domain.

One technical challenge with this merger is the application of the logic expressed previously by Equation 2 and Figure 4 associated with Everything Else that might influence the coating performance. To be successful, we must expand the Everything Else node to contain items that are beyond the coating system selection and the basic observations of performance on the actual FMTV/LMTV assets.

The BBN model predictions for FMTV/LMTV assets are based on the coating system (i.e., surface profile, pretreatment, primer/topcoat), work quality in applying the coating system, key assemblies of parts on the asset, geometric complexity of the assembled parts on the asset, environmental corrosivity, and severity of use of the asset over its life to date. An additional indirect attribute is “time.” Obviously, the older an asset is, meaning the time since the asset was initially built and fielded, the more likely it is to have experienced corrosion. However, time is confounded with the other variables such as the severity of use, and therefore it is not a reliable input parameter. In fact, it can be misleading.

Figure 27 is a BBN that illustrates the prediction flow logic, which combines the inputs to produce a predicted maintenance outcome. The maintenance outcome is based on the number of the assemblies of part classifications with an S.SoC. The model provides the probable number of parts with an S.SoC.

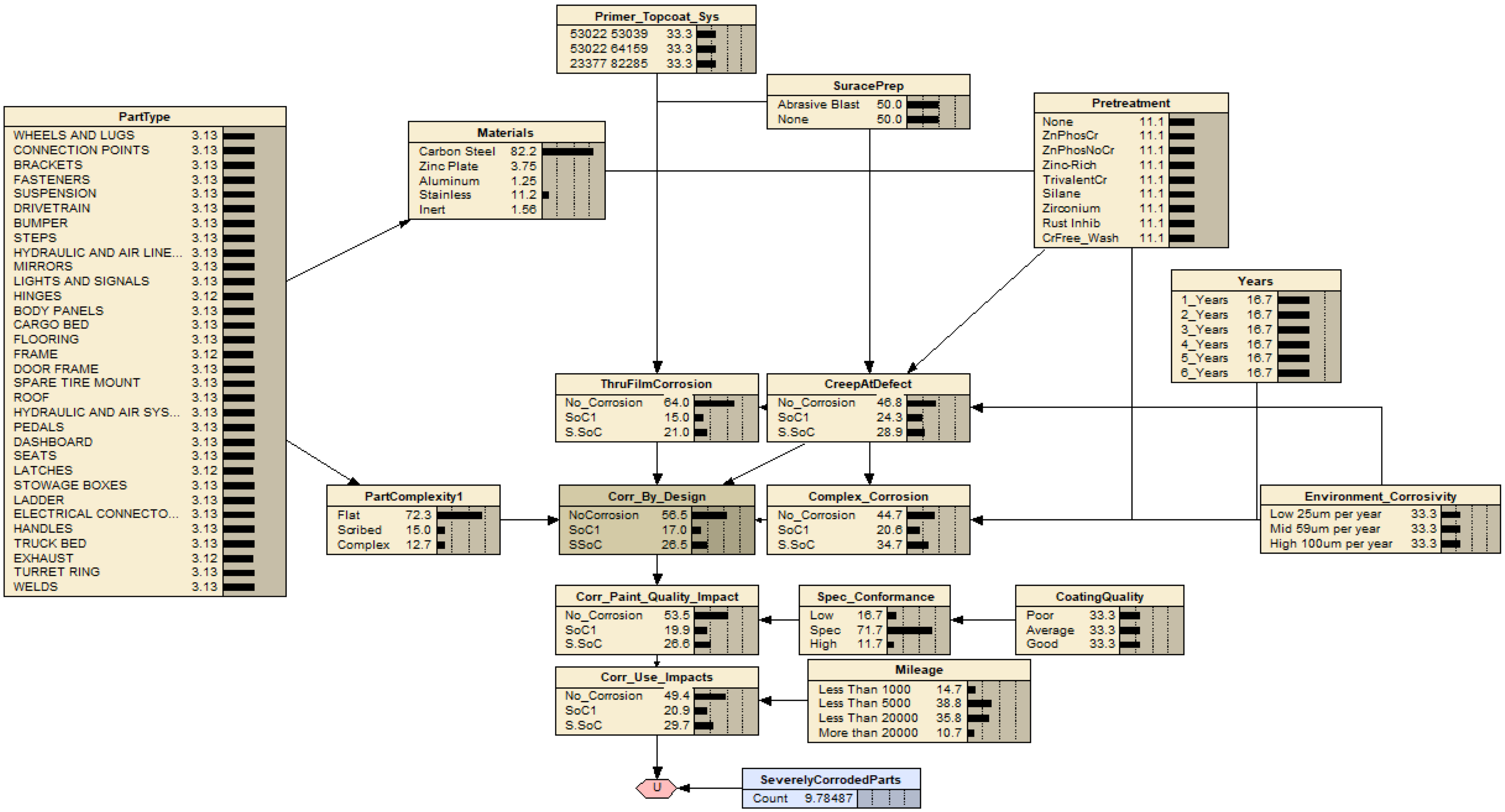


Figure 27. Probabilistic flow logic to arrive at the expected number of part assemblies showing an S.SoC.

The BBN in Figure 28 is simplified to emphasize the flow logic. Some of the chance nodes in the figure are much more involved and really contain their own sub-BBNs, such as the "Part Complexity" node, which includes concepts of the propensity of a part for mechanical damage to the coating system. In this way, a top-level model comprises multiple sub-models.

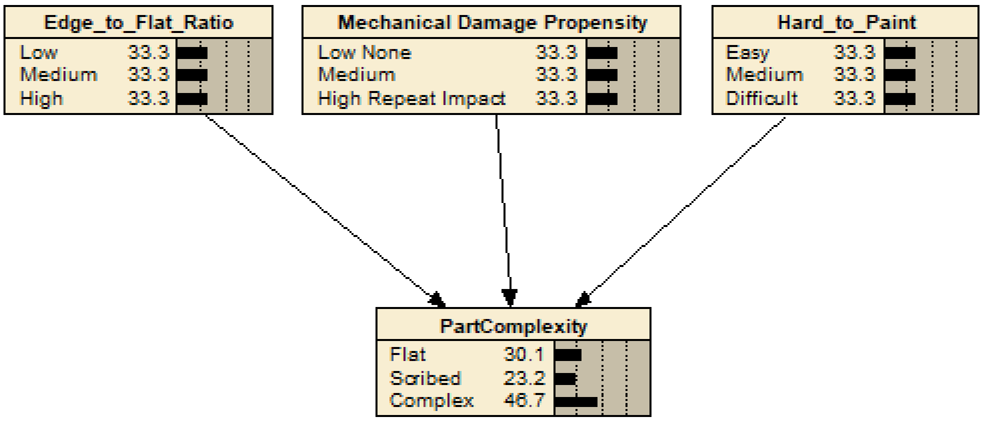


Figure 28. Part complexity Probabilistic Relational Model (PRM).

Within probabilistic modeling, this nesting of models is formally represented using PRMs.[14,15] A PRM is a modeling technique borrowed from object-oriented programming. An existing Bayesian network (BN) is assigned as a "class" or "building block" for a larger BN. Multiple "instances" of the PRM class can be created by copying for use in other modeling as required. The result is a logical structure for developing complex models, because these same PRMs can be used in different combinations.

The model predictions for FMTV/LMTV assets are based on the surface profile, pretreatment, primer/topcoat selections, environment corrosivity, key assemblies of parts, coating quality, and expected mileage. The maintenance classification is based on the number of part assemblies with an S.SoC. The model provides the probable number of parts with an S.SoC.

The model and the associated mathematical relationships were entered into a BBN software tool Netica.[16] The same model (essentially) was also entered into Microsoft Excel for increased ease of manipulation and to share of the concepts with a wider audience using a common software tool. The Excel file is free of macros or any executable code. Appendix F presents this Excel model and a basic guide on its application. The Excel file also shows the embedded CPTs and present values for the input states. Appendix G provides more detailed information on the Netica model.

The model inputs are limited to parameters for which data are available to express impacts on the asset corrosion. The model currently makes simplifying assumptions, such as uniform coating types applied to the entire asset, which is not true. At this time, the variance in coating performance from the ARL data (as discussed below) and a limited ability to trace the exact coating systems, including substrate materials and (possible) plating, limits the value in assigning more specific coatings to each assembly of parts. The approach presented herein can be modified to include such details, should it become available.

The following list describes each of the PRM's that comprise the model of Figures 27 and 28.

1) Basic Coating System. There are five primary inputs regarding the coating system being modeled:
   a) The Surface profile may be either abrasive blasted or mill finish.
   b) The Pretreatment is selected from the following: none, zinc phosphate (chrome rinse), zinc phosphate (nonchrome rinse), zinc-rich, trivalent chrome, silane, zirconium, a flash rust inhibitor, or a chrome free wash primer. (These are generic descriptions provided within the ARL dataset.)
   c) Three organic Primer and Topcoat Systems are evaluated: MIL-DTL-53022[6]/MIL-DTL-53039,[8] MIL-DTL-53022[6]/MIL-DTL-64159,[9] and MIL-PRF-23377[7]/MIL-PRF-85285[10]. These represented systems with significantly available data in the ARL datasets.
   d) The local Environmental Corrosivity is selected from 1, 2.3, or 4 mils/year (25, 59, or 100 μm/year).
   e) The model provides predictions for 1 to 6 years.
2) Expected Coating Performance. The expected coating performance derives from the selected coating system and the projections for through-film corrosion and scribe creep. The screen creep data also serves as the basis for predictions on more complex surfaces. Each is expressed in terms of the expected SoC. Appendix C contains samples of the CPT distributions for these combinations.
3) Part Assemblies and Part Complexity. Each of the 32 key part assemblies are represented in the model. For each part, a material composition was added based on review of the photographic data, inspector input, and knowledge of the part/part material listing for the FMTV. The key part assemblies are themselves combinations of piece parts, and there are certainly variations in the material combinations for each item that might fall within these general classifications. Currently, the model does not

resolve these details. For each part assembly, the following likely conditions combine to create the node Part Complexity:

a) The model includes a node for an Edge-to-Flat Ratio for each part assembly. Appendix F provides a summary of the development of these values. Briefly, they derive from ImageJ analysis of various photographs of sample part assemblies and inspector input.
b) The node for Mechanical Damage Propensity is based on field inspector input and review of part photographs.
c) The Hard-to-Paint node simply distinguishes (primarily) underbody components that present obscured areas in any painting application. Items such as leaf springs will contain many unpainted areas due to the difficulty in painting the individual leaf springs completely.

4) The node Corrosion by Design represents the expected CARC performance, the materials of construction, and the FMTV/LMTV part design complexity.
5) Corrosion due to Paint Quality combines input from Corrosion by Design and Specification Conformance. The Specification Conformance derives from the input of Coating Quality.
6) Corrosion by Use combines the output from Corrosion due to Paint Quality with Mileage. The mileage factor is a term representing the additional coating damage likely to occur from heavy asset use.
7) The S.SoC Part Count expected assembly of part count with NoCorr, SoC1, or S.SoC derives from 32 parts times the projected proportions of each stage. The quantity of S.SoC parts is used to determine the likelihood for the value to represent a maintenance classification of CIC, CIC/Spot Paint, or Repaint. These likelihoods are combined with the prior probability of the dataset to suggest the probable maintenance classification.

4.3.1 Impacts of Pretreatment on Expected Corrosion

The model does suggest an impact on the corrosion observed and the maintenance classification based on the coating systems selected, expected usage (mileage), and paint quality. This model process can be used to identify environmentally beneficial coating systems and processes.

Consider the model set to the following:

- FMTV/LMTV (6 years)
- Local environment corrosivity of 2.3 mils/year (59 µm/year)
- Mill finish
- MIL-DTL-53032/MIL-DTL-53039 coating
- 1,000 to 5,000 miles
- Average coating quality

Table 22 shows the impact of alternative pretreatments when the above parameters are fixed. The data show the immediate benefit of any pretreatment over no pretreatment. The predictions are ordered in terms of increasing predictions of NoCorr. The trend for S.SoC percentages does not perfectly follow this trend, although it does decrease. This seeming disparity relates to the inconsistent performance (i.e., variance) of the test panels with the coating systems.

Table 22. Impact of pretreatment on distribution of SoC.

Pretreatment	NoCorr (%)	SoC1 (%)	S.SoC (%)
None	18	8	74
Zirconium	41	19	40
Chromated wash primer	49	17	34
Trivalent chrome	49	11	40
Zinc phosphate (nonchrome rinse)	52	14	34
Zinc phosphate (chrome rinse)	54	29	17
Flash rust pretreatment	61	6	33
Silane	64	6	30
Zinc rich	87	8	5

4.3.2 Impacts of Coating Variability on Performance

The laboratory coating performance variability impacts the model projections. Significant benefits would be recognized with an increased number of test samples and a basic root-cause failure analysis to explain the variation. This would increase reliability and provide a firm technical basis for assigning additional parameters to the model (e.g., surface profile measurements, film thicknesses, holiday tests, and pretreatment quality). In the absence of the root cause, the explanation becomes speculative.

Figures 13 and 16—the main effects plots for through-film and creepage breakdown of the coatings—show that pretreatments have the primary impact on performance. The organic coating has less impact. The plots showing the performance of the individual organic coatings over each pretreatment (Figures 11, 12, 14, and 15) demonstrate that a different primer/topcoat system shows better performance in each case. The mean performance plotted in the main effects plot shows little average impact of the coating system. The inconsistent, case-to-case performance of the same organic coating system suggests that factors other than the governing MIL-SPEC material choice are influencing the result and the model.

To illustrate this impact, consider the model set to the following:

- FMTV/LMTV (6 years)
- Local environment corrosivity of 2.3 mils/year (59 µm/year)
- Mill finish
- 1,000 to 5,000 miles
- Average coating quality

Table 23 shows the possible variance in the model projections. The data for the zinc-phosphate (chrome rinse) pretreatment are relatively consistent compared with the projections for the same systems over the trivalent chromium pretreatments. For the trivalent chromium pretreatment and the MIL-DTL-53022[6]/MIL-DTL-64159[9] system, only three panels were evaluated. Variation in small datasets can cause large variation in these projections. For the trivalent chromium under the (more common) MIL-DTL-53022[6]/MIL-DTL-53039[8] system, seven panels were evaluated.

Table 23. Impact of pretreatment and coating system on SoC distribution.

Pretreatment	Coating primer/topcoat	NoCorr (%)	SoC1 (%)	S.SoC (%)
Zinc phosphate (chrome rinse)	MIL-DTL-53022[6]/MIL-DTL-53039[8]	53	30	18
Zinc phosphate (chrome rinse)	MIL-DTL-53022[6]/MIL-DTL-64159[9]	62	16	22
Zinc phosphate (chrome rinse)	MIL-PRF-23377[7]/MIL-PRF-82285[10]	68	6	26
Trivalent chromium	MIL-DTL-53022[6]/MIL-DTL-53039[8]	48	11	40
Trivalent chromium	MIL-DTL-53022[6]/MIL-DTL-64159[9]	18	3	79
Trivalent chromium	MIL-PRF-23377[7]/MIL-PRF-82285[10]	35	21	44

4.3.3 Probable Maintenance Classifications

The model can be utilized to consider the probable recommended maintenance. The probable maintenance classification is dominated by two factors: 1) the prior probability, wherein 75.5% of the assets are expected to require spot painting, followed by CIC applications, and 2) the relationship between the S.SoC part count and the maintenance classification (Figure 17). Figure 27 shows the expected number of severely corroded parts.

This is 29.7% (expected S.SoC) of 32-part assemblies and is approximately 9.5 parts (as shown in Figure 27). The likelihood required in Equation 1 is provided by a probability density function described by the shape and scale parameters of Figure 17, which are replotted as a Weibull distribution in Figure 29.*

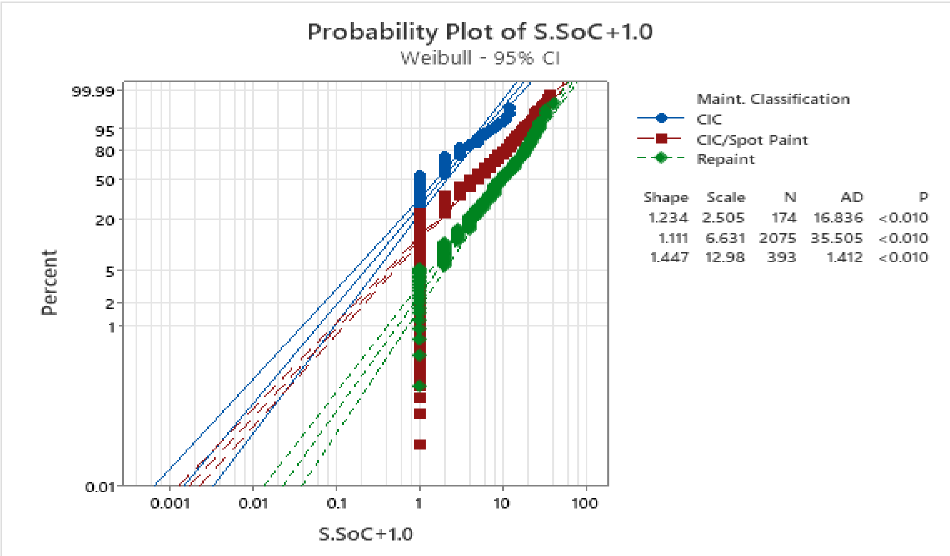


Figure 29. Distribution of the count of S.SoC part assemblies (+1) for each maintenance classification.

Provided with the prior probabilities of 7.5%, 75.5%, and 17% associated with the fleet of assets requiring CIC, CIC/spot painting, and repainting, respectfully, we calculate the posterior probability associated with the knowledge of the count of severely corroded parts.

With the 9.5 severely corroded parts, the likelihood associated with CIC, CIC/spot painting, and repainting is 1.3%, 37.6, and 61.0%. The posterior probability of each would be as follows:

$$P(CIC|9.5\ S.SoC) = \frac{1.3\%\ \times 7.5\%}{1.3\% \times 7.5\% + 37.6\% \times 75.5\% + 61.0\% \times 17\%} = 0.3\% \quad (4)$$

$$P(CIC/Spot|9.5\ S.SoC) = \frac{37.6\%\ \times 75.5\%}{1.3\% \times 7.5\% + 37.6\% \times 75.5\% + 61.0\% \times 17\%} = 73.3\% \quad (5)$$

$$P(Repaint|9.5\ S.SoC) = \frac{61.0\%\ \times 17\%}{1.3\% \times 7.5\% + 37.6\% \times 75.5\% + 61.0\% \times 17\%} = 26.7\%\% \quad (6)$$

A range of calculations can be made for any expected S.SoC count. Increases in the count drive the probable classification toward repainting.

The factor "delamination" appeared to offer some distinction in the projected maintenance classification of assets. The term also appeared to be largely

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* A "1" was added to the S.SoC count to avoid an irrational calculation of the logarithms of zero.

independent of the S.SoC count. The factors driving delamination are not included in the model. There is substantial theory that delamination is the result of "poor" surface preparation including lack of surface pretreatment. As a general concept, this may be correct. However, there are no specific test data for delamination across the CARC system, from surface cleaning to pretreatment primer and topcoat, to demonstrate the probability of the process. Much of the observed delamination also occurs across aluminum or stainless-steel surfaces, and the latter rarely serves as a test bed for the CARC system.

Following the same process applied to the classification afforded by the S.SoC count, the additional information offered by the count of delamination of the parts can be applied to the results of the posterior probabilities from the S.SoC analysis.* Table 24 shows the results of this analysis.

Table 24. Impact of S.SoC part and delamination count on maintenance classification.

		Count: Delamination				
	CIC	**0**	**4**	**8**	**16**	**32**
Count: S.SoC	0	40%	10%	3%	0%	0%
	4	16%	3%	1%	0%	0%
	8	3%	0%	0%	0%	0%
	16	0%	0%	0%	0%	0%
	32	0%	0%	0%	0%	0%

		Count: Delamination				
	CIC/Spot	**0**	**4**	**8**	**16**	**32**
Count: S.SoC	0	57%	86%	91%	80%	9%
	4	75%	86%	83%	62%	4%
	8	80%	81%	75%	49%	2%
	16	68%	67%	59%	31%	1%
	32	45%	44%	36%	15%	0%

		Count: Delamination				
	Repaint	**0**	**4**	**8**	**16**	**32**
Count: S.SoC	0	3%	5%	7%	20%	91%
	4	10%	11%	16%	38%	96%
	8	17%	19%	24%	51%	98%
	16	32%	33%	41%	69%	99%
	32	55%	56%	64%	85%	100%

4.3.4 Probable Maintenance Indicators

The primary maintenance indicator is the corrosion of the most visible components. Often, these are the lowest value parts (fasteners, brackets, etc.) common to many Army systems. Although they may be of a lower value, they are telltale signs for

* The order of operations in the application of the likelihoods to the prior probabilities does not matter mathematically.

the probability of corrosion in other areas of the asset. A summary of these correlations is presented in Appendix G. Our findings suggest that field inspections might focus on those assets with the more visible forms of corrosion on the common parts to find higher-value parts that might also be corroding. Simply, it is assumed that corrosion of the low-value parts is indicative of use and exposure to corrosive conditions that are more likely to drive corrosion on all aspects of the asset.

5. Conclusions

The average magnitude of corrosion observed on fielded assets can be modeled based on laboratory testing of coating systems. However, several factors affecting fielded items are not evaluated in most laboratory tests. Most specifically, these include mechanical damage to coatings, variations in the (physical) coating stack-up, and the propensity for delamination.

- There would be a benefit to improve coating resistance to the physical stress on Army ground systems, such as chipping from stones and fine grit. As modeled, there is a substantial influence of abrasion/mechanical damage to existing coatings.
- In the field, coating application to complex surfaces results in substantial differences in film quality versus laboratory testing. Such impacts are not commonly studied in a systematic process. The evaluation of coatings should include sufficient variance to better predict real-world applications.
- Coating delamination appears to be a separate issue from substrate corrosion. This suggests that the delamination is from aluminum, galvanized, or stainless-steel surfaces. It is also possible that the delamination of a topcoat is from a contrasting color primer, which still offers some corrosion protection. Delamination is typically assumed to result from improper surface preparation/pretreatment application or substrate contamination. However, no large dataset relates such factors to delamination, which limits modeling.

Model accuracy and forecasting of positive or negative outcomes are limited by unresolved variance in coating performance data. No single, specific, CARC primer/topcoat combination had a consistent performance advantage, despite outstanding performance in a specific coating stack-up. The lack of consistency suggests a process that is not tightly controlled. Additional knowledge in this area may increase modeling and real-world performance.

The primary drivers increasing the degree of corrosion control maintenance seem to be related to the more severe forms of the SoC and areas of coating delamination. Corrosion of steel parts is increased by vehicle use and exposure to physical stress.

Minor corrosion (SoC1) is ubiquitous on part assemblies and does not differentiate the required level of maintenance (CIC, CIC/Spot Paint, Repaint).

Corrosion of prominent, visible parts on the FMTV/LMTV is an indicator of probable corrosion on other components. Such corrosion observations can aid in condition-based maintenance planning for corrosion control.

6. References

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Appendix A. Through-Film Corrosion and Creep at Defects

The following tables illustrate the mathematical concepts discussed in the main body of the report. Specifically, Table A-1 demonstrates how the expected through-film corrosion from each test panel was used to establish the expected range of corrosion observations over a multiyear period. The process considers both the anticipated incubation time (time to first sign of corrosion through the film) followed by the growth of the corrosion phenomena. Table A-2 shows how the data in Table A-1 are summarized to predict the Conditional Probability Table or expected mean behavior of this particular coating system over time. Table A-3 summarizes the process for estimating the appearance of panels as a result of corrosion creep from a defect in the coating system.

Table A-1. Calculations for expected proportion of Stages of Corrosion ratings (SoC), MIL-DTL-53022[1] primer, and MIL-DTL-53039[2] topcoat over abrasive blasted steel without any pretreatment.

Total time of exposure (year)[a]	Started growing in year	Has grown for years	Proportion of population post incubation[b]	Expected proportion of SoC based on growth years					Expected proportion of SoC × proportion corroding for observation year and growth time[c]				
				NoCorr	SoC1	SoC2	SoC3	SoC4	NoCorr	SoC1	SoC2	SoC3	SoC4
1	1	1	0.11	0.27	0.64	0.00	0.09	0.00	0.03[d]	0.07	. . .	0.01	. . .
2	1	2	0.11	0.09	0.64	0.09	0.09	0.09	0.01	0.07	0.01	0.01	0.01
2	2	1	0.62	0.27	0.64	0.00	0.09	0.00	0.17	0.39	. . .	0.06	. . .
3	1	3	0.11	0.00	0.55	0.18	0.00	0.27	. . .	0.06	0.02	. . .	0.03
3	2	2	0.62	0.09	0.64	0.09	0.09	0.09	0.06	0.39	0.06	0.06	0.06
3	3	1	0.27	0.27	0.64	0.00	0.09	0.00	0.07	0.17	. . .	0.02	. . .
4	1	4	0.11	0.00	0.18	0.55	0.00	0.27	. . .	0.02	0.06	. . .	0.03
4	2	3	0.62	0.00	0.55	0.18	0.00	0.27	. . .	0.34	0.11	. . .	0.17
4	3	2	0.27	0.09	0.64	0.09	0.09	0.09	0.02	0.17	0.02	0.02	0.02
4	4	1	0.00	0.27	0.64	0.00	0.09	0.00	0.00	0.00	. . .	0.00	. . .
5	1	5	0.11	0.00	0.18	0.55	0.00	0.27	. . .	0.02	0.06	. . .	0.03
5	2	4	0.62	0.00	0.18	0.55	0.00	0.27	. . .	0.11	0.34	. . .	0.17
5	3	3	0.27	0.00	0.55	0.18	0.00	0.27	. . .	0.15	0.05	. . .	0.07
5	4	2	0.00	0.09	0.64	0.09	0.09	0.09	0.00	0.00	0.00	0.00	0.00
5	5	1	0.00	0.27	0.64	0.00	0.09	0.00	0.00	0.00	. . .	0.00	. . .
6	1	6	0.11	0.00	0.00	0.64	0.09	0.27	. . .	. . .	0.07	0.01	0.03
6	2	5	0.62	0.00	0.18	0.55	0.00	0.27	. . .	0.11	0.34	. . .	0.17
6	3	4	0.27	0.00	0.18	0.55	0.00	0.27	. . .	0.05	0.15	. . .	0.07
6	4	3	0.00	0.00	0.55	0.18	0.00	0.27	. . .	0.00	0.00	. . .	0.00
6	5	2	0.00	0.09	0.64	0.09	0.09	0.09	0.00	0.00	0.00	0.00	0.00
6	6	1	0.00	0.27	0.64	0.00	0.09	0.00	0.00	0.00	. . .	0.00	. . .

Notes: NoCorr = No Corrosion or coating failure; SoC1/2/3/4 = Stage(s) of Corrosion rating 1/2/3/4.

[a] Add the quantities for each total time of exposure.

[b] Weibull Shape/Scale = 3.49 and 22.3 (months). Cumulative distribution function is $1 - e^{-(\frac{x}{Scale})^{Shape}}$. At 12 months or 1 year, expected postincubation would be 0.11. At 24 months, this would be 0.73. Given that 0.11 appeared in year 1, 0.62 occurred in year 2. Repeat for each year.

[c] The total of these proportions does not include the coating not past the incubation point. Add this proportion to the NoCorr value (see Table A-2).

[d] Top line: 0.11 × 0.27 = 0.03, 0.11 × 0.64 = 0.07, etc.

[1] MIL-DTL-53022. Primer, epoxy coating, corrosion inhibiting lead and chromate free. Department of Defense (US); 2021 Apr 15.

[2] MIL-DTL-53039. Camouflage coating, solvent based, chemical agent resistant. Department of Defense (US); 2022.

Table A-2. Summary of expected proportion of SoC, MIL-DTL-53022[1] primer, and MIL-DTL-53039[2] topcoat over abrasive blasted steel without any pretreatment, years 1 and 2 (from Table A-1).

Total time of exposure (year)	Expected distribution of ratings					Total (past incubation)	Not past incubation
	NoCorr	SoC1	SoC2	SoC3	SoC4		
1	0.92[a]	0.07	. . .	0.01	. . .	. . .	. . .
2	0.45[a]	0.46	0.01	0.07	0.01	. . .	. . .
. . .	Expected proportion of SoC × proportion corroding for observation year and growth time					. . .	. . .
1	0.03[a]	0.07	. . .	0.01	. . .	. . .	. . .
	0.03	0.07	. . .	0.01	. . .	0.11	0.89[a]
2	0.01	0.07	0.01	0.01	0.01	. . .	. . .
2	0.17	0.39	. . .	0.06	. . .	. . .	. . .
. . .	0.18[a]	0.46	0.01	0.07	0.01	0.73	0.27[a]

[a] Example: The projected NoCorr is the sum of those expected panels without observable corrosion, 0.03, plus those portions of the panels that have yet to reach the incubation time, 0.89.

Table A-3. Example of estimated SoC based on creepage data, abrasive blasted steel, no pretreatment, MIL-DTL-53022[1] primer, and MIL-DTL-53039[2] topcoat.

Total exposure time (yr)	%Samples <2.5 mm creep	Incremental growth (%population) >2.5 mm	Started growing in year	Total corrosion (µm)	NoCorr	SoC1	SoC2	SoC3+
1	0.73	0.27	1	25	0.73	0.27	. . .	. . .
2	. . .	0.73	2	25	. . .	0.73	. . .	. . .
2	. . .	0.27	1	50		0.27	. . .	. . .
3	. . .	. . .	3	25	. . .	. . .	. . .	. . .
3	. . .	0.73	2	50		0.73	. . .	. . .
3	. . .	0.27	1	75		0.27	. . .	. . .
4	. . .	. . .	4	25	. . .	. . .	. . .	. . .
4	. . .	. . .	3	50		. . .	. . .	. . .
4	. . .	0.73	2	75		0.73	. . .	. . .
4	. . .	0.27	1	100		0.27	. . .	. . .
5	. . .	. . .	5	25	. . .	. . .	. . .	. . .
5	. . .	. . .	4	50		. . .	. . .	. . .
5	. . .	. . .	3	75		. . .	. . .	. . .
5	. . .	0.73	2	100		0.73	. . .	. . .
5	. . .	0.27	1	125		0.27	. . .	. . .
6	. . .	. . .	6	25		. . .	. . .	. . .
6	. . .	. . .	5	50		. . .	. . .	. . .
6	. . .	. . .	4	75		. . .	. . .	. . .
6	. . .	. . .	3	100	. . .	. . .	. . .	. . .
6	. . .	0.73	2	125		0.73	. . .	. . .
6	. . .	0.27	1	150		. . .	0.27	. . .

Appendix B. Part Assembly Photographs

The following pages present photographs of key part assemblies that show the style and complexity of the surfaces inspected.

Figure B-1. Brackets.

Figure B-2. Connection points.

Figure B-3. Electrical connectors and components.

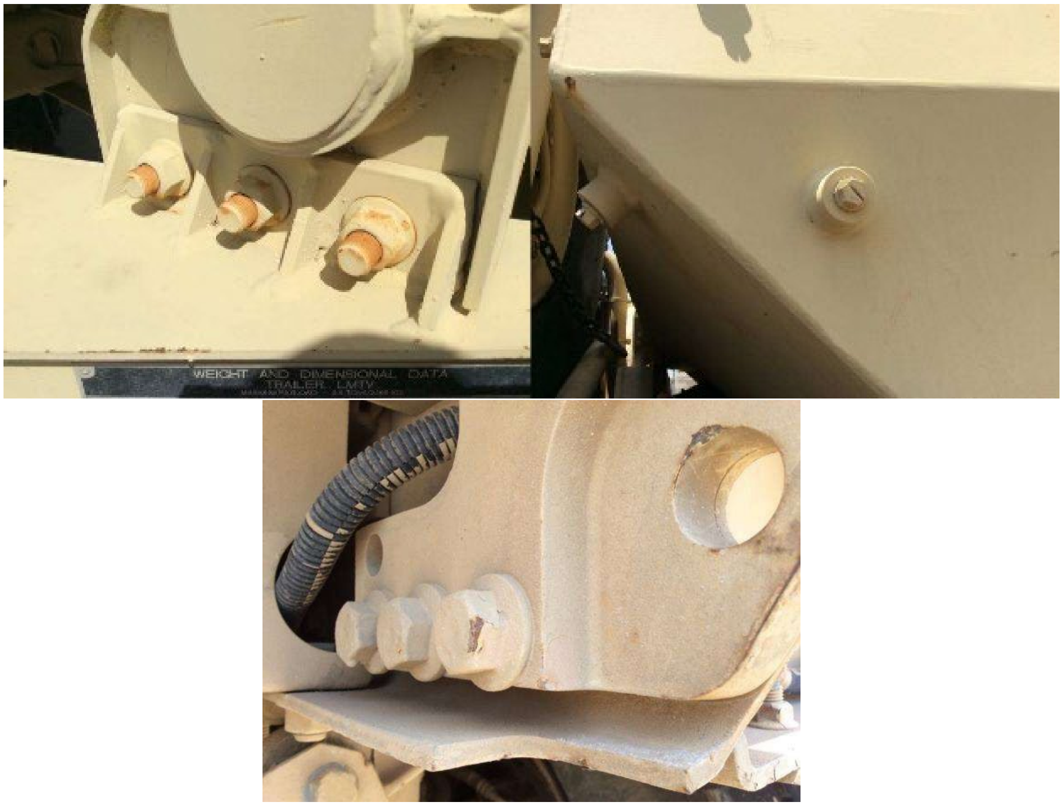


Figure B-4. Fasteners.

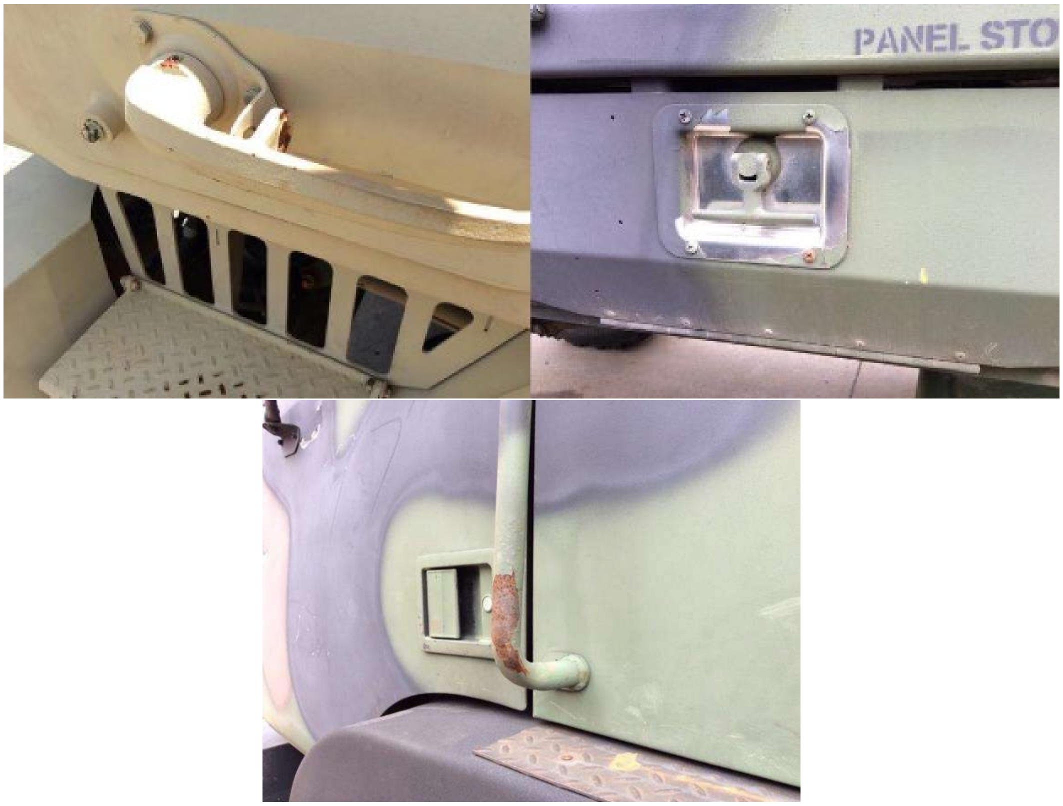


Figure B-5. Handles.

Figure B-6. Hinges.

Figure B-7. Hydraulics and air lines and connections.

Figure B-8. Hydraulic and air systems.

Figure B-9. Hydraulic and air tanks.

Figure B-10. Lights and signals.

Figure B-11. Welds.

Figure B-12. Wheels and lugs.

Figure B-13. Body panels.

Figure B-14. Bumper.

Figure B-15. Cargo bed.

Figure B-16. Door frame.

Figure B-17. Drivetrain.

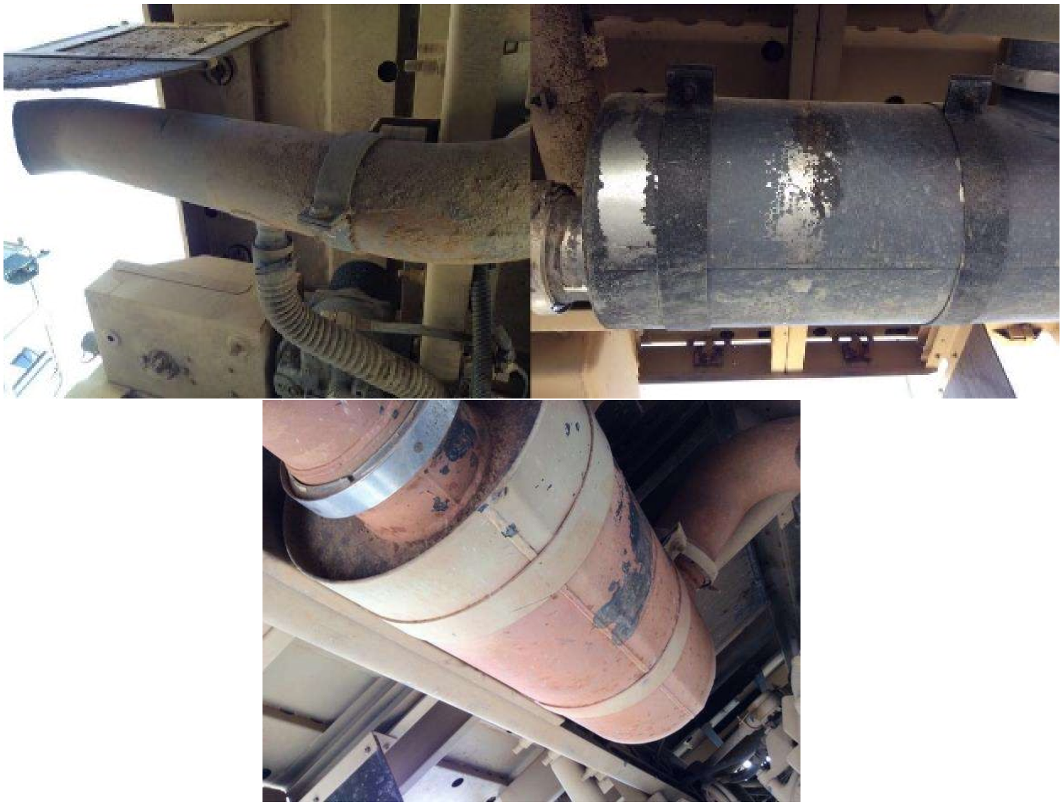


Figure B-18. Exhaust.

Figure B-19. Flooring.

Figure B-20. Frame.

Figure B-21. Roof.

Figure B-22. Spare tire mount.

Figure B-23. Steps.

Figure B-24. Stowage boxes.

Figure B-25. Suspension.

Figure B-26. Turret ring.

Appendix C. Stage of Corrosion (SoC) Distributions via Through-Film Corrosion and Creep

Tables C-1 to C-3 show the various conditional probability tables for specific combinations of surface profile, pretreatments, and specific primer/topcoat system combinations. These predictions are based on the procedures described in the modeling approach and utilize the U.S. Army Combat Capabilities Development Command Army Research Laboratory dataset.

Tables C-4 to C-6 show the same concepts for corrosion via creep from a coating defect. These projections are for the condition wherein the local corrosivity is 59 µm/year. The results would be less corrosive at the 25 µm/year corrosion rate and higher at the 100 µm/year corrosion rate. Abbreviations for the tables are as follows: NoCorr = expectations of No Corrosion or coating failure; SoC1/2/3 = Stage(s) of Corrosion rating 1/2/3; SoC3+ = SoC3 and SoC4.

Table C-1. Probability distribution of through-film corrosion for MIL-DTL-53022[1]/MIL-DTL-53039[2] by surface profile and pretreatment.

Probability (0 - 1.0 [i.e. 0 to 100%])

			MIL-DTL-53022[1]/MIL-DTL-53039[2] coating system											
			Zinc phosphate with chrome rinse				**Zinc phosphate with nonchrome rinse**				**No pretreatment**			
			NoCorr	**SoC1**	**SoC2**	**SoC3+**	**NoCorr**	**SoC1**	**SoC2**	**SoC3+**	**NoCorr**	**SoC1**	**SoC2**	**SoC3+**
Mill finish	**Present year**	1	1.00	0.00	. . .	. . .	0.99	0.00	0.00	. . .	. . .	. . .	. . .	. . .
		2	1.00	0.00	. . .	. . .	0.96	0.03	0.01	. . .	. . .	. . .	. . .	. . .
		3	0.99	0.01	. . .	. . .	0.88	0.08	0.04	0.00	Not tested			
		4	0.91	0.09	. . .	. . .	0.77	0.12	0.10	0.01	. . .	. . .	. . .	. . .
		5	0.69	0.31	. . .	. . .	0.67	0.13	0.17	0.03	. . .	. . .	. . .	. . .
		6	0.67	0.33	. . .	. . .	0.60	0.11	0.21	0.08	. . .	. . .	. . .	. . .
Abrasive blast	**Present year**	1	1.00	. . .	. . .	. . .	1.00	0.00	. . .	. . .	0.73	0.24	. . .	0.03
		2	1.00	. . .	. . .	. . .	0.99	0.01	0.00	0.00	0.29	0.56	0.03	0.11
		3	1.00	. . .	. . .	. . .	0.94	0.05	0.01	0.00	0.08	0.60	0.11	0.20
		4	1.00	. . .	. . .	. . .	0.85	0.11	0.02	0.02	0.01	0.42	0.30	0.26
		5	1.00	. . .	. . .	. . .	0.71	0.17	0.04	0.07	0.00	0.23	0.50	0.27
		6	1.00	. . .	. . .	. . .	0.58	0.20	0.06	0.17	0.00	0.12	0.58	0.30
			Silane pretreatment				**Trivalent chromium pretreatment**				**Zinc rich**			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill finish	**Present year**	1	1.00	. . .	0.00	. . .	1.00	0.00	. . .	. . .	1.00	. . .	. . .	. . .
		2	0.98	. . .	0.02	. . .	0.99	0.01	0.00	. . .	1.00	. . .	. . .	. . .
		3	0.95	. . .	0.05	. . .	0.84	0.15	0.00	0.00	1.00	. . .	. . .	. . .
		4	0.91	. . .	0.09	. . .	0.67	0.25	0.08	0.00	1.00	. . .	. . .	. . .
		5	0.89	. . .	0.11	. . .	0.61	0.18	0.13	0.08	1.00	. . .	. . .	. . .
		6	0.87	. . .	0.13	. . .	0.61	0.13	0.13	0.13	1.00	. . .	. . .	. . .
Abrasive Blast	**Present Year**	1	0.70	0.30	. . .	. . .	0.69	0.31	. . .	. . .	. . .	. . .	. . .	. . .
		2	0.48	0.52	. . .	. . .	0.24	0.66	0.05	0.05	. . .	. . .	. . .	. . .
		3	0.34	0.49	0.17	. . .	0.05	0.47	0.32	0.17	Not tested			
		4	0.25	0.45	0.30	. . .	0.01	0.12	0.56	0.31	. . .	. . .	. . .	. . .
		5	0.20	0.38	0.42	. . .	0.00	0.01	0.58	0.40	. . .	. . .	. . .	. . .
		6	0.16	0.33	0.46	0.04	0.00	0.00	0.57	0.43	. . .	. . .	. . .	. . .

[1] MIL-DTL-53022. Primer, epoxy coating, corrosion inhibiting lead and chromate free. Department of Defense (US); 2021 Apr 15.
[2] MIL-DTL-53039. Camouflage coating, solvent based, chemical agent resistant. Department of Defense (US); 2022.

Table C-2. Probability distribution of through-film corrosion for MIL-DTL-53022[1]/MIL-DTL-64159[3] by surface profile and pretreatment.

				MIL-DTL-53022 / MIL-DTL-64159 Coating System											
				Zinc Phosphate with Chrome Rinse				**Zinc Phosphate with Non-Chrome Rinse**				**No Pretreatment**			
				NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Probability (0 - 1.0 [i.e. 0 to 100%])	Mill Finish	Present Year	1	1.00	0.00	-	-	1.00	0.00	-	-				
			2	1.00	0.00	-	-	1.00	0.00	0.00	-				
			3	0.98	0.02	-	-	0.96	0.04	0.00	-		Not tested		
			4	0.95	0.05	-	-	0.85	0.13	0.02	0.00				
			5	0.89	0.11	-	-	0.74	0.19	0.07	0.00				
			6	0.80	0.20	-	-	0.72	0.15	0.11	0.02				
	Abrasive Blast	Present Year	1	1.00	0.00	0.00	-	1.00	0.00	0.00	-	1.00	0.00	0.00	-
			2	1.00	0.00	0.00	-	0.97	0.01	0.02	-	0.88	0.04	0.08	0.00
			3	0.97	0.01	0.01	-	0.92	0.03	0.05	0.00	0.42	0.21	0.25	0.12
			4	0.87	0.06	0.07	0.00	0.84	0.06	0.09	0.01	0.17	0.25	0.08	0.50
			5	0.68	0.12	0.20	0.00	0.74	0.09	0.13	0.03	0.17	0.00	0.33	0.50
			6	0.54	0.11	0.33	0.02	0.64	0.13	0.16	0.07	0.17	0.00	0.25	0.58
				Silane Pretreatment				**Trivalent Chromium Pretreatment**				**Zinc-Rich**			
				NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
	Mill Finish	Present Year	1	1.00	-	-	-	1.00	0.00	-	-				
			2	1.00	-	-	-	0.13	0.87	0.00	-				
			3	1.00	-	-	-	0.00	0.42	0.58	0.00		Not tested		
			4	1.00	-	-	-	0.01	0.33	0.09	0.57				
			5	1.00	-	-	-	0.00	0.04	0.29	0.67				
			6	1.00	-	-	-	-	-	0.33	0.67				
	Abrasive Blast	Present Year	1	1.00	-	-	-	1.00	0.00	0.00	-				
			2	1.00	-	-	-	1.00	0.00	0.00	-				
			3	1.00	-	-	-	0.12	0.58	0.29	0.00		Not tested		
			4	1.00	-	-	-	0.00	0.08	0.92	0.00				
			5	1.00	-	-	-	0.00	(0.00)	0.71	0.29				
			6	1.00	-	-	-	0.01	(0.00)	0.37	0.62				

[3] MIL-DTL-64159. Camouflage coating, water dispersible chemical agent resistant. Department of Defense (US); 2022 Mar 24.

Table C-3. Probability distribution of through-film corrosion for MIL-PRF-23377[4]/MIL-PRF-85285[5] by surface profile and pretreatment.

Probability (0 - 1.0 [i.e. 0 to 100%])

			MIL-PRF-23377 / MIL-PRF-85285 Coating System											
			Zinc Phosphate with Chrome Rinse				Zinc Phosphate with Non-Chrome Rinse				No Pretreatment			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	1.00	-	-	-	1.00	-	-	-				
Mill Finish	Present Year	2	1.00	-	-	-	0.99	0.01	-	-				
Mill Finish	Present Year	3	1.00	-	-	-	0.90	0.10	0.01	-		Not tested		
Mill Finish	Present Year	4	1.00	-	-	-	0.71	0.19	0.10	-				
Mill Finish	Present Year	5	1.00	-	-	-	0.67	0.04	0.29	0.01				
Mill Finish	Present Year	6	1.00	-	-	-	0.67	0.00	0.23	0.10				
Abrasive Blast	Present Year	1	0.99	0.01	-	-	1.00	0.00	-	-	0.98	0.01	-	0.01
Abrasive Blast	Present Year	2	0.92	0.08	0.00	-	0.94	0.06	0.00	-	0.38	0.31	0.00	0.31
Abrasive Blast	Present Year	3	0.78	0.20	0.02	0.00	0.32	0.67	0.01	-	0.33	0.18	0.16	0.33
Abrasive Blast	Present Year	4	0.58	0.34	0.07	0.02	0.21	0.64	0.15	0.00	0.18	0.32	0.01	0.49
Abrasive Blast	Present Year	5	0.36	0.45	0.12	0.07	0.10	0.34	0.55	0.01	0.17	0.33	-	0.50
Abrasive Blast	Present Year	6	0.19	0.51	0.14	0.16	0.01	0.44	0.41	0.14	0.17	0.33	0.00	0.50
			Silane Pretreatment				Trivalent Chromium Pretreatment				Zinc-Rich			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	1.00	-	0.00	-	1.00	0.00	-	-				
Mill Finish	Present Year	2	0.71	-	0.29	0.00	0.96	0.04	-	-				
Mill Finish	Present Year	3	0.38	-	0.33	0.29	0.67	0.33	-	-		Not tested		
Mill Finish	Present Year	4	0.33	-	0.04	0.63	0.63	0.37	0.00	-				
Mill Finish	Present Year	5	0.33	-	0.00	0.67	0.33	0.63	0.04	-				
Mill Finish	Present Year	6	0.33	-	0.00	0.67	0.34	0.33	0.33	0.00				
Abrasive Blast	Present Year	1	1.00	0.00	-	-	1.00	-	-	-				
Abrasive Blast	Present Year	2	0.38	0.62	0.00	-	1.00	-	-	-				
Abrasive Blast	Present Year	3	0.00	0.79	0.21	0.00	1.00	0.00	-	-		Not tested		
Abrasive Blast	Present Year	4	-	0.25	0.54	0.20	0.98	0.02	-	-				
Abrasive Blast	Present Year	5	0.00	0.00	0.67	0.33	0.90	0.10	-	-				
Abrasive Blast	Present Year	6	0.01	0.00	0.46	0.54	0.77	0.23	-	-				

[4] MIL-PRF-23377. Primer coatings: epoxy, high-solids. Department of Defense (US); 2019 Sep 12.
[5] MIL-PRF-85285. Topcoat, aircraft and support equipment. Department of Defense (US); 2024 Dec 10.

Table C-4. Probability distribution of corrosion via creep for MIL-DTL-53022[1]/MIL-DTL-53039[2] by surface profile and pretreatment.

Probability (0 - 1.0 [i.e. 0 to 100%])

MIL-DTL-53022 / MIL-DTL-53039 Coating System

			Zinc Phosphate with Chrome Rinse				Zinc Phosphate with Non-Chrome Rinse				No Pretreatment			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	1.00	-	-	-	0.75	0.25	-	-	Not tested			
		2	0.83	0.17	-	-	0.50	0.25	0.25	-				
		3	0.83	-	0.17	-	0.50	-	0.25	0.25				
		4	0.50	0.33	-	0.17	0.50	-	-	0.50				
		5	0.50	-	0.33	0.17	0.50	-	-	0.50				
		6	-	0.50	-	0.50	0.25	0.25	-	0.50				
Abrasive Blast	Present Year	1	1.00	-	-	-	1.00	-	-	-	0.73	0.27	-	-
		2	0.83	0.17	-	-	0.78	0.22	-	-	-	0.73	0.27	-
		3	0.83	-	0.17	-	0.78	-	0.22	-	-	-	0.73	0.27
		4	0.83	-	-	0.17	0.78	-	-	0.22	-	-	-	1.00
		5	0.50	0.33	-	0.17	0.56	0.22	-	0.22	-	-	-	1.00
		6	0.33	0.17	0.33	0.17	0.22	0.34	0.22	0.22	-	-	-	1.00

			Silane Pretreatment				Trivalent Chromium Pretreatment				Zinc-Rich			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	0.25	0.75	-	-	0.25	0.75	-	-	Not tested			
		2	0.13	0.87	-	-	-	1.00	-	-				
		3	0.13	0.12	0.75	-	-	0.25	0.75	-				
		4	0.13	-	0.87	-	-	-	1.00	-				
		5	0.13	-	0.12	0.75	-	-	0.25	0.75				
		6	0.13	-	-	0.87	-	-	-	1.00				
Abrasive Blast	Present Year	1	1.00	-	-	-	1.00	-	-	-	1.00	-	-	-
		2	0.63	0.37	-	-	0.86	0.14	-	-	1.00	-	-	-
		3	0.25	0.75	-	-	0.57	0.43	-	-	1.00	-	-	-
		4	0.13	0.50	0.37	-	0.57	0.29	0.14	-	1.00	-	-	-
		5	0.13	0.12	0.75	-	0.29	0.28	0.43	-	1.00	-	-	-
		6	0.13	-	0.50	0.37	-	0.57	0.29	0.14	1.00	-	-	-

Table C-5. Probability distribution of corrosion via creep for MIL-DTL-53022[1]/MIL-DTL-64159[3] by surface profile and pretreatment.

Probability (0 - 1.0 [i.e. 0 to 100%])

			MIL-DTL-53022 / MIL-DTL-64159 Coating System											
			Zinc Phosphate with Chrome Rinse				Zinc Phosphate with Non-Chrome Rinse				No Pretreatment			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	1.00	-	-	-	0.71	0.29	-	-				
		2	0.33	0.67	-	-	0.43	0.28	0.29	-				
		3	-	0.33	0.67	-	0.43	-	0.28	0.29		Not tested		
		4	-	-	0.33	0.67	0.43	-	-	0.57				
		5	-	-	-	1.00	0.43	-	-	0.57				
		6	-	-	-	1.00	0.43	-	-	0.57				
Abrasive Blast	Present Year	1	1.00	-	-	-	1.00	-	-	-	1.00	-	-	-
		2	0.50	0.50	-	-	0.67	0.33	-	-	-	1.00	-	-
		3	-	0.50	0.50	-	0.67	-	0.33	-	-	-	1.00	-
		4	-	-	0.50	0.50	0.67	-	-	0.33	-	-	-	1.00
		5	-	-	-	1.00	0.56	0.11	-	0.33	-	-	-	1.00
		6	-	-	-	1.00	0.44	0.12	0.11	0.33	-	-	-	1.00

			Silane Pretreatment				Trivalent Chromium Pretreatment				Zinc-Rich			
			NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	Present Year	1	-	1.00	-	-	-	1.00	-	-				
		2	-	1.00	-	-	-	1.00	-	-				
		3	-	-	1.00	-	-	-	1.00	-		Not tested		
		4	-	-	1.00	-	-	-	1.00	-				
		5	-	-	-	1.00	-	-	-	1.00				
		6	-	-	-	1.00	-	-	-	1.00				
Abrasive Blast	Present Year	1	1.00	-	-	-	1.00	-	-	-				
		2	1.00	-	-	-	1.00	-	-	-				
		3	-	1.00	-	-	0.67	0.33	-	-		Not tested		
		4	-	1.00	-	-	0.67	0.33	-	-				
		5	-	-	1.00	-	0.67	-	0.33	-				
		6	-	-	1.00	-	0.67	-	0.33	-				

Table C-6. Probability distribution of corrosion via creep for MIL-PRF-23377[4]/MIL-PRF-85285[5] by surface profile and pretreatment.

Probability (0 - 1.0 [i.e. 0 to 100%])

		MIL-PRF-23377 / MIL-PRF-85285 Coating System											
		Zinc Phosphate with Chrome Rinse				Zinc Phosphate with Non-Chrome Rinse				No Pretreatment			
Surface Profile	Present Year	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	1	1.00	-	-	-	0.57	0.43	-	-				
	2	0.33	0.67	-	-	0.57	-	0.43	-				
	3	0.33	-	0.67	-	0.14	0.43	-	0.43		Not tested		
	4	0.33	-	-	0.67	0.14	-	0.43	0.43				
	5	0.33	-	-	0.67	0.14	-	-	0.86				
	6	0.33	-	-	0.67	0.14	-	-	0.86				
Abrasive Blast	1	1.00	-	-	-	1.00	-	-	-	0.33	0.67	-	-
	2	1.00	-	-	-	0.78	0.22	-	-	-	0.33	0.67	-
	3	0.50	0.50	-	-	0.78	-	0.22	-	-	-	0.33	0.67
	4	0.50	-	0.50	-	0.78	-	-	0.22	-	-	-	1.00
	5	0.33	0.17	-	0.50	0.67	0.11	-	0.22	-	-	-	1.00
	6	0.33	-	0.17	0.50	0.56	0.11	0.11	0.22	-	-	-	1.00

		Silane Pretreatment				Trivalent Chromium Pretreatment				Zinc-Rich			
Surface Profile	Present Year	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+	NoCorr	SoC1	SoC2	SoC3+
Mill Finish	1	0.67	0.33	-	-	-	1.00	-	-				
	2	-	1.00	-	-	-	1.00	-	-				
	3	-	0.67	0.33	-	-	-	1.00	-		Not tested		
	4	-	-	1.00	-	-	-	1.00	-				
	5	-	-	0.67	0.33	-	-	-	1.00				
	6	-	-	-	1.00	-	-	-	1.00				
Abrasive Blast	1	1.00	-	-	-	1.00	-	-	-				
	2	0.67	0.33	-	-	1.00	-	-	-				
	3	-	1.00	-	-	0.67	0.33	-	-		Not tested		
	4	-	0.67	0.33	-	0.67	0.33	-	-				
	5	-	-	1.00	-	0.33	0.34	0.33	-				
	6	-	-	0.67	0.33	0.33	0.34	0.33	-				

Appendix D. Fort Dix Detailed Inspection Data of Family of Medium Tactical Vehicles (FMTV) Assets

The following provides the raw data and additional details concerning the detailed inspection of FMTV assets at Fort Dix, New Jersey. These inspections are intended to complement the larger field inspection database by gathering more detailed data on dry film thickness (DFT), holiday propensity, and signs of abrasion/mechanical damage.

Table D-1 summarizes the observations of part use (in general) for the specific asset, the part assemblies inspected, the specific percentage of each Stage of Corrosion (SoC) (SoC 4 rating [SoC4] was not observed), and the percentage of coating delamination. During these detailed inspections, the SoC was reported as the actual percentage of the affected area. There was no minimum area requirement of 5%, as in the more general and much larger field data. Table D-2 provides the average film thickness (mils) and signs of abrasion specific to the individual part assembly.

Table D-1. FMTV inspections, Fort Dix, summary of use, SoC, and delamination observations.

FMTV asset ID	Date of manufacture (month/year)	Area	Part assembly	%Parts showing use	SoC 1%	SoC 2%	SoC 3%	%Coating delamination
10TANHFF2FS722962	05/15	Under	Suspension	46	3	7	. . .	1
10TANHFF2FS722962	05/15	Front	Lights and Signals	46	4	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Driver	Body Panel	46	. . .	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Pass	Body Panel	46	. . .	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Pass	Stowage Box	46	. . .	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Front	Welds	46	2	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Top	Roof	46	. . .	. . .	. . .	. . .
10TANHFF2FS722962	05/15	Top	Hatch	46	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Under	Suspension	8	. . .	2	. . .	. . .
10TANHFE5J5782420	06/18	Front	Lights and Signals	8	. . .	0.5	. . .	. . .
10TANHFE5J5782420	06/18	Driver	Body Panel	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Pass	Body Panel	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Rear	Cargo Bed	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Driver	Stowage Box	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Pass	Stowage Box	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Front	Welds	8	1	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Rear	Body Panel	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Top	Roof	8	. . .	. . .	. . .	. . .
10TANHFE5J5782420	06/18	Top	Hatch	8	. . .	. . .	. . .	1
10TDJAU56B5725308	06/11	Under	Suspension	67	3	. . .	. . .	1
10TDJAU56B5725308	06/11	Front	Lights and Signals	67	10	3	. . .	. . .
10TDJAU56B5725308	06/11	Driver	Body Panel	67	1	1	. . .	. . .
10TDJAU56B5725308	06/11	Pass	Body Panel	67	. . .	1	. . .	. . .
10TDJAU56B5725308	06/11	Rear	Cargo Bed	67	0.5	0.5	. . .	1
10TDJAU56B5725308	06/11	Driver	Stowage Box	67	4	. . .	. . .	. . .
10TDJAU56B5725308	06/11	Pass	Stowage Box	67	. . .	1	. . .	. . .
10TDJAU56B5725308	06/11	Front	Welds	67	. . .	2	. . .	. . .
10TDJAU56B5725308	06/11	Rear	Body Panel	67	2	5	. . .	. . .
10TDJAU56B5725308	06/11	Top	Roof	67	. . .	. . .	. . .	. . .
10TDJAU56B5725308	06/11	Top	Hatch	67	. . .	. . .	. . .	. . .

Table D-1. FMTV inspections, Fort Dix, summary of use, SoC, and delamination observations (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part assembly	%Parts showing use	SoC 1%	SoC 2%	SoC 3%	%Coating delamination
10TANHFF9ES769278	04/14	Under	Suspension	38	12	5	. . .	. . .
10TANHFF9ES769278	04/14	Front	Lights and Signals	38	30	5	. . .	. . .
10TANHFF9ES769278	04/14	Driver	Body Panel	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Pass	Body Panel	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Rear	Cargo Bed	38	1	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Driver	Stowage Box	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Pass	Stowage Box	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Front	Welds	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Rear	Body Panel	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Top	Roof	38	. . .	. . .	. . .	. . .
10TANHFF9ES769278	04/14	Top	Hatch	38	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Under	Suspension	42	2	5	. . .	. . .
10TANHFE4JS782439	06/18	Front	Lights and Signals	42	10	3	. . .	. . .
10TANHFE4JS782439	06/18	Driver	Body Panel	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Pass	Body Panel	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Rear	Cargo Bed	42	1	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Driver	Stowage Box	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Pass	Stowage Box	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Front	Welds	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Rear	Body Panel	42	0.5	1	. . .	. . .
10TANHFE4JS782439	06/18	Top	Roof	42	. . .	. . .	. . .	. . .
10TANHFE4JS782439	06/18	Top	Hatch	42	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Under	Suspension	54	15	3	0.5	. . .
10TANHFF5E5769276	04/14	Front	Lights and Signals	54	7	1	. . .	. . .
10TANHFF5E5769276	04/14	Driver	Body Panel	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Pass	Body Panel	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Rear	Cargo Bed	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Driver	Stowage Box	54	. . .	1	. . .	. . .
10TANHFF5E5769276	04/14	Pass	Stowage Box	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Front	Welds	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Rear	Body Panel	54	0.5	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Top	Roof	54	. . .	. . .	. . .	. . .
10TANHFF5E5769276	04/14	Top	Hatch	54	. . .	. . .	. . .	. . .
DXD209788E4BW	03/10	Under	Suspension	88	10	5	5	. . .
DXD209788E4BW	03/10	Front	Lights and Signals	88	2	. . .	. . .	1
DXD209788E4BW	03/10	Driver	Body Panel	88	. . .	. . .	. . .	. . .
DXD209788E4BW	03/10	Pass	Body Panel	88	. . .	. . .	. . .	. . .
DXD209788E4BW	03/10	Rear	Cargo Bed	88	1	2	. . .	. . .
DXD209788E4BW	03/10	Pass	Stowage Box	88	. . .	. . .	. . .	. . .
DXD209788E4BW	03/10	Front	Welds	88	5	5	. . .	. . .
DXD209788E4BW	03/10	Rear	Body Panel	88	. . .	1	. . .	. . .
DXD209788E4BW	03/10	Top	Roof	88	1	. . .	. . .	. . .
DXD209788E4BW	03/10	Top	Hatch	88	. . .	2	. . .	1

Table D-1. FMTV inspections, Fort Dix, summary of use, SoC, and delamination observations (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part assembly	%Parts showing use	SoC 1%	SoC 2%	SoC 3%	%Coating delamination
10TANHFFXCS742085	05/12	Under	Suspension	50	15	20	. . .	. . .
10TANHFFXCS742085	05/12	Front	Lights and Signals	50	2	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Driver	Body Panel	50	0.5	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Pass	Body Panel	50	. . .	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Rear	Cargo Bed	50	3	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Pass	Stowage Box	50	0.5	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Front	Welds	50	1	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Rear	Body Panel	50	2	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Top	Roof	50	. . .	. . .	. . .	. . .
10TANHFFXCS742085	05/12	Top	Hatch	50	. . .	. . .	. . .	3
10TANHFE2JS782410	06/18	Under	Suspension	13	43	1	. . .	. . .
10TANHFE2JS782410	06/18	Front	Lights and Signals	13	5	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Driver	Body Panel	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Pass	Body Panel	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Rear	Cargo Bed	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Driver	Stowage Box	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Pass	Stowage Box	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Front	Welds	13	4	2	. . .	. . .
10TANHFE2JS782410	06/18	Top	Roof	13	. . .	. . .	. . .	. . .
10TANHFE2JS782410	06/18	Rear	Body Panel	13	. . .	2	. . .	. . .
10TANHFE2JS782410	06/18	Top	Hatch	13	. . .	. . .	. . .	1
10TANHFE6CS740745	04/24	Under	Suspension		15	7	. . .	2
10TANHFE6CS740745	04/24	Front	Lights and Signals	50	1	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Driver	Body Panel	50	. . .	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Pass	Body Panel	50	. . .	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Rear	Cargo Bed	50	. . .	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Driver	Stowage Box	50	. . .	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Pass	Stowage Box	50	4	1	. . .	2
10TANHFE6CS740745	04/24	Front	Welds	50	1	1	. . .	. . .
10TANHFE6CS740745	04/24	Top	Roof	50	. . .	. . .	. . .	. . .
10TANHFE6CS740745	04/24	Rear	Body Panel	50	7	2	. . .	3
10TANHFE6CS740745	04/24	Top	Hatch	50	. . .	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Under	Suspension	29	9	1	. . .	1
10TANHFF3CS732157	11/11	Front	Lights and Signals	29	2	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Driver	Body Panel	29	. . .	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Pass	Body Panel	29	. . .	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Pass	Stowage Box	29	1	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Front	Welds	29	0.5	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Top	Roof	29	. . .	. . .	. . .	. . .
10TANHFF3CS732157	11/11	Top	Hatch	29	. . .	. . .	. . .	0.5

Table D-1. FMTV inspections, Fort Dix, summary of use, SoC, and delamination observations (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part assembly	%Parts showing use	SoC 1%	SoC 2%	SoC 3%	%Coating delamination
A-E703698EHFV	09/09	Under	Suspension	50	4	1.5	. . .	1
A-E703698EHFV	09/09	Front	Lights and Signals	50	1	. . .	. . .	. . .
A-E703698EHFV	09/09	Driver	Body Panel	50	. . .	. . .	. . .	0.5
A-E703698EHFV	09/09	Pass	Body Panel	50	. . .	3	. . .	. . .
A-E703698EHFV	09/09	Rear	Cargo Bed	50	. . .	. . .	. . .	. . .
A-E703698EHFV	09/09	Driver	Stowage Box	50	1	. . .	. . .	. . .
A-E703698EHFV	09/09	Pass	Stowage Box	50	. . .	. . .	. . .	8
A-E703698EHFV	09/09	Front	Welds	50	3	0.5	. . .	0.5
A-E703698EHFV	09/09	Top	Roof	50	. . .	. . .	. . .	. . .
A-E703698EHFV	09/09	Rear	Body Panel	50	. . .	. . .	. . .	. . .
A-E703698EHFV	09/09	Top	Hatch	50	. . .	. . .	. . .	. . .
A-D70934137EHAW	02/10	Under	Suspension	67	8	4	. . .	3
A-D70934137EHAW	02/10	Front	Lights and Signals	67	3	5	. . .	. . .
A-D70934137EHAW	02/10	Driver	Body Panel	67	. . .	1	. . .	. . .
A-D70934137EHAW	02/10	Pass	Body Panel	67	1	. . .	. . .	. . .
A-D70934137EHAW	02/10	Rear	Cargo Bed	67	. . .	. . .	. . .	. . .
A-D70934137EHAW	02/10	Driver	Stowage Box	67	. . .	. . .	. . .	. . .
A-D70934137EHAW	02/10	Pass	Stowage Box	67	0.5	. . .	. . .	. . .
A-D70934137EHAW	02/10	Front	Welds	67	8	0.5	. . .	. . .
A-D70934137EHAW	02/10	Top	Roof	67	. . .	. . .	. . .	. . .
A-D70934137EHAW	02/10	Rear	Body Panel	67	. . .	4	. . .	. . .
A-D70934137EHAW	02/10	Top	Hatch	67	2	3	1	. . .
B-D709684EHBW	02/10	Under	Suspension	50	3	2	. . .	8
B-D709684EHBW	02/10	Front	Lights and Signals	50	2	. . .	. . .	. . .
B-D709684EHBW	02/10	Driver	Body Panel	50	. . .	. . .	. . .	. . .
B-D709684EHBW	02/10	Pass	Body Panel	50	0.5	. . .	. . .	. . .
B-D709684EHBW	02/10	Rear	Cargo Bed	50	. . .	2	. . .	3
B-D709684EHBW	02/10	Driver	Stowage Box	50	. . .	. . .	. . .	. . .
B-D709684EHBW	02/10	Pass	Stowage Box	50	. . .	. . .	. . .	1
B-D709684EHBW	02/10	Front	Welds	50	2	0.5	. . .	. . .
B-D709684EHBW	02/10	Top	Roof	50	1	. . .	. . .	. . .
B-D709684EHBW	02/10	Rear	Body Panel	50	. . .	6	. . .	. . .
B-D709684EHBW	02/10	Top	Hatch	50	. . .	. . .	. . .	1
10TANHFF5CS736677	03/12	Under	Suspension	46	5	1	. . .	. . .
10TANHFF5CS736677	03/12	Front	Lights and Signals	46	. . .	. . .	. . .	. . .
10TANHFF5CS736677	03/12	Driver	Body Panel	46	. . .	. . .	. . .	. . .
10TANHFF5CS736677	03/12	Pass	Body Panel	46	. . .	. . .	. . .	. . .
10TANHFF5CS736677	03/12	Rear	Cargo Bed	46	. . .	1	. . .	. . .
10TANHFF5CS736677	03/12	Pass	Stowage Box	46	1	2	. . .	. . .
10TANHFF5CS736677	03/12	Front	Welds	46	. . .	. . .	. . .	2
10TANHFF5CS736677	03/12	Top	Roof	46	. . .	. . .	. . .	. . .
10TANHFF5CS736677	03/12	Rear	Body Panel	46	1	1	. . .	. . .
10TANHFF5CS736677	03/12	Top	Hatch	46	. . .	. . .	. . .	. . .

Table D-1. FMTV inspections, Fort Dix, summary of use, SoC, and delamination observations (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part assembly	%Parts showing use	SoC 1%	SoC 2%	SoC 3%	%Coating delamination
10TANHFF2CS736670	03/12	Under	Suspension	42	7	1	. . .	. . .
10TANHFF2CS736670	03/12	Front	Lights and Signals	42	2	. . .	. . .	. . .
10TANHFF2CS736670	03/12	Driver	Body Panel	42	. . .	2	. . .	. . .
10TANHFF2CS736670	03/12	Rear	Cargo Bed	42	. . .	. . .	. . .	. . .
10TANHFF2CS736670	03/12	Pass	Body Panel	42	. . .	. . .	. . .	. . .
10TANHFF2CS736670	03/12	Pass	Stowage Box	42	2	. . .	. . .	. . .
10TANHFF2CS736670	03/12	Front	Welds	42	4	2	. . .	3
10TANHFF2CS736670	03/12	Top	Roof	42	. . .	. . .	. . .	. . .
10TANHFF2CS736670	03/12	Rear	Body Panel	42	1	1	. . .	. . .
10TANHFF2CS736670	03/12	Top	Hatch	42	. . .	. . .	. . .	. . .

Table D-2. FMTV inspections, Fort Dix, average DFT, and signs of abrasion on the specific part.

FMTV asset ID	Date of manufacture (month/year)	Area	Part	Average part DFT	Abrasion/ impact
10TANHFF2FS722962	05/15	Under	Suspension	8.81	. . .
10TANHFF2FS722962	05/15	Front	Lights and Signals	3.01	. . .
10TANHFF2FS722962	05/15	Driver	Body Panel	5.97	. . .
10TANHFF2FS722962	05/15	Pass	Body Panel	5.45	. . .
10TANHFF2FS722962	05/15	Pass	Stowage Box	7.63	. . .
10TANHFF2FS722962	05/15	Front	Welds	NA	. . .
10TANHFF2FS722962	05/15	Top	Roof	6.08	. . .
10TANHFF2FS722962	05/15	Top	Hatch	5.42	. . .
10TANHFE5J5782420	06/18	Under	Suspension	7.04	. . .
10TANHFE5J5782420	06/18	Front	Lights and Signals	4.74	. . .
10TANHFE5J5782420	06/18	Driver	Body Panel	6.06	. . .
10TANHFE5J5782420	06/18	Pass	Body Panel	7.30	. . .
10TANHFE5J5782420	06/18	Rear	Cargo Bed	7.18	. . .
10TANHFE5J5782420	06/18	Driver	Stowage Box	6.00	. . .
10TANHFE5J5782420	06/18	Pass	Stowage Box	6.55	. . .
10TANHFE5J5782420	06/18	Front	Welds	NA	. . .
10TANHFE5J5782420	06/18	Rear	Body Panel	6.15	1
10TANHFE5J5782420	06/18	Top	Roof	6.82	. . .
10TANHFE5J5782420	06/18	Top	Hatch	7.16	. . .
10TDJAU56B5725308	06/11	Under	Suspension	5.95	. . .
10TDJAU56B5725308	06/11	Front	Lights and Signals	4.92	. . .
10TDJAU56B5725308	06/11	Driver	Body Panel	13.99	. . .
10TDJAU56B5725308	06/11	Pass	Body Panel	12.04	. . .
10TDJAU56B5725308	06/11	Rear	Cargo Bed	6.82	. . .
10TDJAU56B5725308	06/11	Driver	Stowage Box	4.77	. . .
10TDJAU56B5725308	06/11	Pass	Stowage Box	6.32	. . .
10TDJAU56B5725308	06/11	Front	Welds	NA	1
10TDJAU56B5725308	06/11	Rear	Body Panel	4.75	1
10TDJAU56B5725308	06/11	Top	Roof	13.81	. . .
10TDJAU56B5725308	06/11	Top	Hatch	6.38	. . .

Table D-2. FMTV inspections, Fort Dix, average DFT, and signs of abrasion on the specific part (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part	Average part DFT	Abrasion/ impact
10TANHFF9ES769278	04/14	Under	Suspension	6.34	1
10TANHFF9ES769278	04/14	Front	Lights and Signals	2.57	. . .
10TANHFF9ES769278	04/14	Driver	Body Panel	6.58	. . .
10TANHFF9ES769278	04/14	Pass	Body Panel	7.15	. . .
10TANHFF9ES769278	04/14	Rear	Cargo Bed	6.20	1
10TANHFF9ES769278	04/14	Driver	Stowage Box	5.28	. . .
10TANHFF9ES769278	04/14	Pass	Stowage Box	7.30	. . .
10TANHFF9ES769278	04/14	Front	Welds	NA	. . .
10TANHFF9ES769278	04/14	Rear	Body Panel	6.39	. . .
10TANHFF9ES769278	04/14	Top	Roof	8.41	. . .
10TANHFF9ES769278	04/14	Top	Hatch	5.98	. . .
10TANHFE4JS782439	06/18	Under	Suspension	6.98	. . .
10TANHFE4JS782439	06/18	Front	Lights and Signals	3.05	. . .
10TANHFE4JS782439	06/18	Driver	Body Panel	7.12	. . .
10TANHFE4JS782439	06/18	Pass	Body Panel	7.13	. . .
10TANHFE4JS782439	06/18	Rear	Cargo Bed	6.31	. . .
10TANHFE4JS782439	06/18	Driver	Stowage Box	7.27	. . .
10TANHFE4JS782439	06/18	Pass	Stowage Box	7.94	. . .
10TANHFE4JS782439	06/18	Front	Welds	NA	1
10TANHFE4JS782439	06/18	Rear	Body Panel	6.71	1
10TANHFE4JS782439	06/18	Top	Roof	8.51	. . .
10TANHFE4JS782439	06/18	Top	Hatch	6.86	. . .
10TANHFF5E5769276	04/14	Under	Suspension	7.11	. . .
10TANHFF5E5769276	04/14	Front	Lights and Signals	3.31	. . .
10TANHFF5E5769276	04/14	Driver	Body Panel	8.54	. . .
10TANHFF5E5769276	04/14	Pass	Body Panel	8.91	. . .
10TANHFF5E5769276	04/14	Rear	Cargo Bed	7.71	. . .
10TANHFF5E5769276	04/14	Driver	Stowage Box	5.10	1
10TANHFF5E5769276	04/14	Pass	Stowage Box	7.15	. . .
10TANHFF5E5769276	04/14	Front	Welds	NA	1
10TANHFF5E5769276	04/14	Rear	Body Panel	6.19	. . .
10TANHFF5E5769276	04/14	Top	Roof	8.31	. . .
10TANHFF5E5769276	04/14	Top	Hatch	5.43	. . .
DXD209788E4BW	03/10	Under	Suspension	4.99	. . .
DXD209788E4BW	03/10	Front	Lights and Signals	5.53	. . .
DXD209788E4BW	03/10	Driver	Body Panel	5.60	. . .
DXD209788E4BW	03/10	Pass	Body Panel	4.85	. . .
DXD209788E4BW	03/10	Rear	Cargo Bed	4.95	1
DXD209788E4BW	03/10	Pass	Stowage Box	2.88	1
DXD209788E4BW	03/10	Front	Welds	NA	1
DXD209788E4BW	03/10	Rear	Body Panel	7.45	1
DXD209788E4BW	03/10	Top	Roof	5.40	. . .
DXD209788E4BW	03/10	Top	Hatch	3.36	. . .

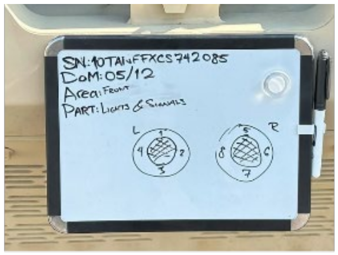
Table D-2. FMTV inspections, Fort Dix, average DFT, and signs of abrasion on the specific part (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part	Average part DFT	Abrasion/ impact
10TANHFFXCS742085	05/12	Under	Suspension	10.26	. . .
10TANHFFXCS742085	05/12	Front	Lights and Signals	7.03	. . .
10TANHFFXCS742085	05/12	Driver	Body Panel	8.91	. . .
10TANHFFXCS742085	05/12	Pass	Body Panel	9.29	. . .
10TANHFFXCS742085	05/12	Rear	Cargo Bed	5.73	1
10TANHFFXCS742085	05/12	Pass	Stowage Box	6.89	. . .
10TANHFFXCS742085	05/12	Front	Welds	NA	. . .
10TANHFFXCS742085	05/12	Rear	Body Panel	8.18	1
10TANHFFXCS742085	05/12	Top	Roof	8.29	. . .
10TANHFFXCS742085	05/12	Top	Hatch	7.43	. . .
10TANHFE2JS782410	06/18	Under	Suspension	7.00	. . .
10TANHFE2JS782410	06/18	Front	Lights and Signals	6.38	. . .
10TANHFE2JS782410	06/18	Driver	Body Panel	6.96	. . .
10TANHFE2JS782410	06/18	Pass	Body Panel	6.42	. . .
10TANHFE2JS782410	06/18	Rear	Cargo Bed	7.18	. . .
10TANHFE2JS782410	06/18	Driver	Stowage Box	4.45	. . .
10TANHFE2JS782410	06/18	Pass	Stowage Box	7.23	. . .
10TANHFE2JS782410	06/18	Front	Welds	NA	1
10TANHFE2JS782410	06/18	Top	Roof	7.10	. . .
10TANHFE2JS782410	06/18	Rear	Body Panel	7.38	. . .
10TANHFE2JS782410	06/18	Top	Hatch	7.23	. . .
10TANHFE6CS740745	04/24	Under	Suspension	7.10	. . .
10TANHFE6CS740745	04/24	Front	Lights and Signals	5.73	. . .
10TANHFE6CS740745	04/24	Driver	Body Panel	8.05	. . .
10TANHFE6CS740745	04/24	Pass	Body Panel	7.53	. . .
10TANHFE6CS740745	04/24	Rear	Cargo Bed	7.61	. . .
10TANHFE6CS740745	04/24	Driver	Stowage Box	7.08	. . .
10TANHFE6CS740745	04/24	Pass	Stowage Box	7.10	. . .
10TANHFE6CS740745	04/24	Front	Welds	NA	. . .
10TANHFE6CS740745	04/24	Top	Roof	7.23	. . .
10TANHFE6CS740745	04/24	Rear	Body Panel	8.26	. . .
10TANHFE6CS740745	04/24	Top	Hatch	6.31	. . .
10TANHFF3CS732157	11/11	Under	Suspension	7.61	. . .
10TANHFF3CS732157	11/11	Front	Lights and Signals	5.45	. . .
10TANHFF3CS732157	11/11	Driver	Body Panel	8.39	. . .
10TANHFF3CS732157	11/11	Pass	Body Panel	7.21	. . .
10TANHFF3CS732157	11/11	Pass	Stowage Box	5.74	. . .
10TANHFF3CS732157	11/11	Front	Welds	NA	. . .
10TANHFF3CS732157	11/11	Top	Roof	7.56	. . .
10TANHFF3CS732157	11/11	Top	Hatch	5.98	. . .
A-E703698EHFV	09/09	Under	Suspension	10.75	. . .
A-E703698EHFV	09/09	Front	Lights and Signals	7.20	. . .
A-E703698EHFV	09/09	Driver	Body Panel	8.60	. . .
A-E703698EHFV	09/09	Pass	Body Panel	6.26	. . .
A-E703698EHFV	09/09	Rear	Cargo Bed	8.03	. . .
A-E703698EHFV	09/09	Driver	Stowage Box	4.56	. . .
A-E703698EHFV	09/09	Pass	Stowage Box	6.72	. . .
A-E703698EHFV	09/09	Front	Welds	NA	. . .
A-E703698EHFV	09/09	Top	Roof	7.89	. . .
A-E703698EHFV	09/09	Rear	Body Panel	6.27	. . .

Table D-2. FMTV inspections, Fort Dix, average DFT, and signs of abrasion on the specific part (continued).

FMTV asset ID	Date of manufacture (month/year)	Area	Part	Average part DFT	Abrasion/ impact
A-E703698EHFV	09/09	Top	Hatch	7.14	. . .
A-D70934137EHAW	02/10	Under	Suspension	4.33	. . .
A-D70934137EHAW	02/10	Front	Lights and Signals	3.19	. . .
A-D70934137EHAW	02/10	Driver	Body Panel	5.75	. . .
A-D70934137EHAW	02/10	Pass	Body Panel	5.40	1
A-D70934137EHAW	02/10	Rear	Cargo Bed	3.48	. . .
A-D70934137EHAW	02/10	Driver	Stowage Box	2.31	. . .
A-D70934137EHAW	02/10	Pass	Stowage Box	3.45	. . .
A-D70934137EHAW	02/10	Front	Welds	NA	. . .
A-D70934137EHAW	02/10	Top	Roof	5.15	. . .
A-D70934137EHAW	02/10	Rear	Body Panel	3.38	1
A-D70934137EHAW	02/10	Top	Hatch	6.81	1
B-D709684EHBW	02/10	Under	Suspension	4.22	. . .
B-D709684EHBW	02/10	Front	Lights and Signals	6.14	. . .
B-D709684EHBW	02/10	Driver	Body Panel	5.99	. . .
B-D709684EHBW	02/10	Pass	Body Panel	6.19	. . .
B-D709684EHBW	02/10	Rear	Cargo Bed	2.84	. . .
B-D709684EHBW	02/10	Driver	Stowage Box	2.69	. . .
B-D709684EHBW	02/10	Pass	Stowage Box	4.15	. . .
B-D709684EHBW	02/10	Front	Welds	NA	. . .
B-D709684EHBW	02/10	Top	Roof	5.57	. . .
B-D709684EHBW	02/10	Rear	Body Panel	2.73	1
B-D709684EHBW	02/10	Top	Hatch	4.16	. . .
10TANHFF5CS736677	03/12	Under	Suspension	8.07	. . .
10TANHFF5CS736677	03/12	Front	Lights and Signals	5.02	. . .
10TANHFF5CS736677	03/12	Driver	Body Panel	9.16	. . .
10TANHFF5CS736677	03/12	Pass	Body Panel	8.93	. . .
10TANHFF5CS736677	03/12	Rear	Cargo Bed	5.96	. . .
10TANHFF5CS736677	03/12	Pass	Stowage Box	5.91	1
10TANHFF5CS736677	03/12	Front	Welds	NA	. . .
10TANHFF5CS736677	03/12	Top	Roof	8.04	1
10TANHFF5CS736677	03/12	Rear	Body Panel	6.05	1
10TANHFF5CS736677	03/12	Top	Hatch	6.98	1
10TANHFF2CS736670	03/12	Under	Suspension	8.46	. . .
10TANHFF2CS736670	03/12	Front	Lights and Signals	5.35	. . .
10TANHFF2CS736670	03/12	Driver	Body Panel	9.60	1
10TANHFF2CS736670	03/12	Rear	Cargo Bed	6.28	. . .
10TANHFF2CS736670	03/12	Pass	Body Panel	9.00	. . .
10TANHFF2CS736670	03/12	Pass	Stowage Box	6.06	. . .
10TANHFF2CS736670	03/12	Front	Welds	NA	. . .
10TANHFF2CS736670	03/12	Top	Roof	7.76	. . .
10TANHFF2CS736670	03/12	Rear	Body Panel	5.91	. . .
10TANHFF2CS736670	03/12	Top	Hatch	6.27	. . .

Figures D-1 to D-10 show photographs of the part assemblies, indicating the physical size of the parts and the locations for film thickness and (edge) holiday testing. On flat areas, the film thickness measurements and holiday tests were made over the general broad surface.



- 8 DFT locations
- No holiday testing

Figure D-1. Lights and signals.

- 9 DFT locations
- Area = 532 in^2
- Holiday edge length testing 37 in (red line)

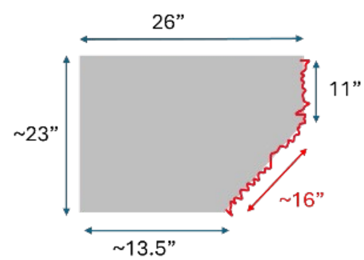
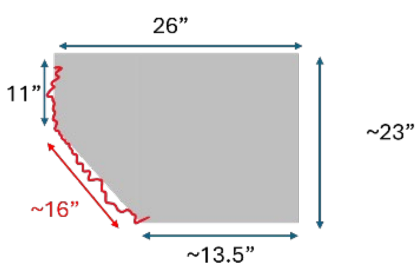
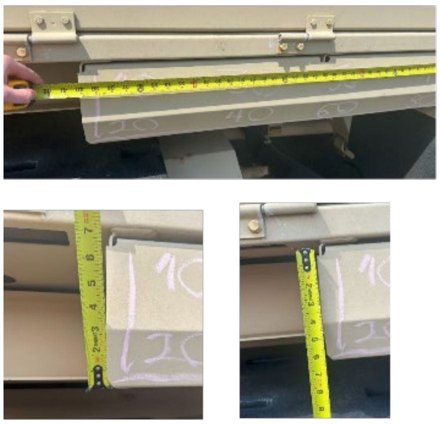


Figure D-2. Driver’s side body panel.



- 9 DFT locations
- Area = 532 in^2
- Holiday edge length testing 37 in (red line)

Figure D-3. Passenger’s side body panel.



- Area = 280 in^2
- Holiday edge length testing 54 in (red line)

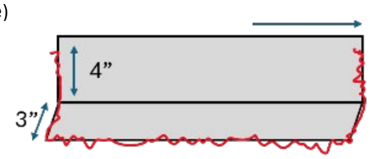
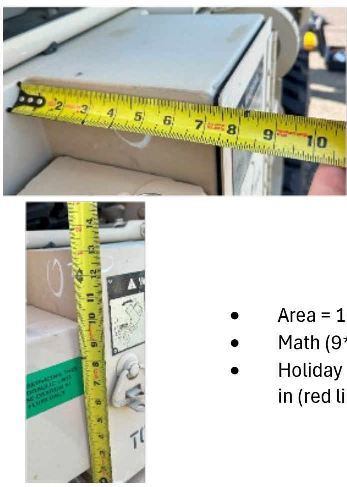
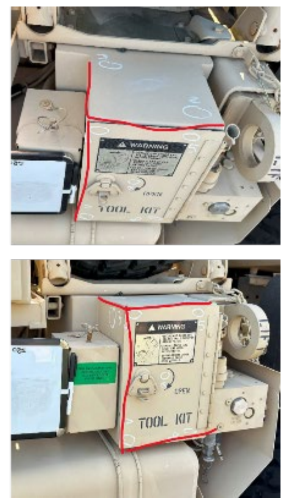


Figure D-4. Driver’s side storage box.





- Area = 160.75 in^2
- Math (9*7)+((9*13)-(5.5*3.5))
- Holiday edge length testing 45 in (red line)

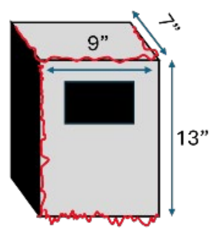


Figure D-5. Passenger’s side stowage box.

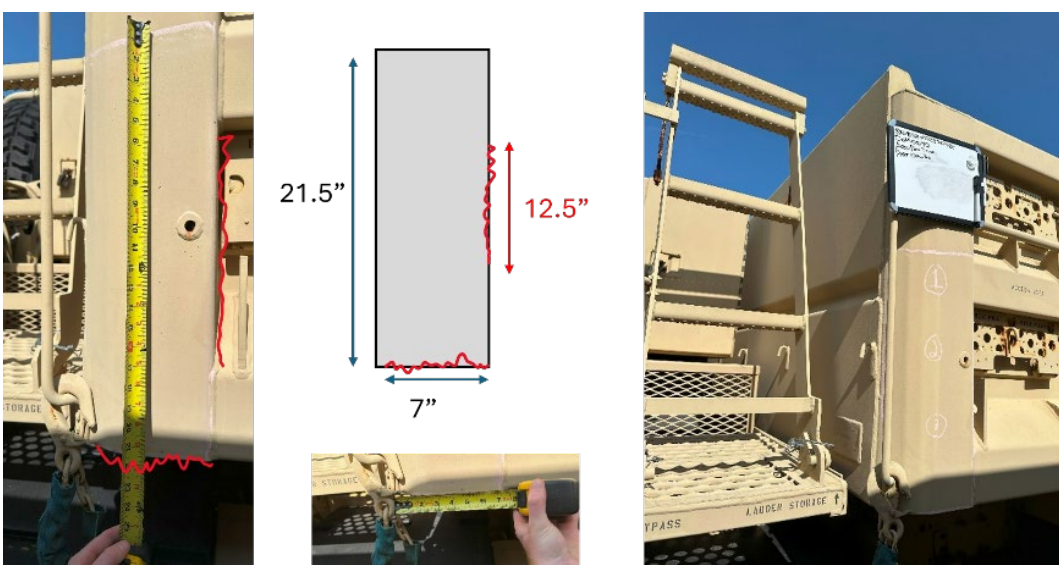


Figure D-6. Rear cargo bed door.

- Area = 90 in^2
- 6 DFT locations
- Holiday edge length testing 30 in (red line)

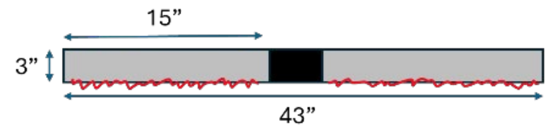
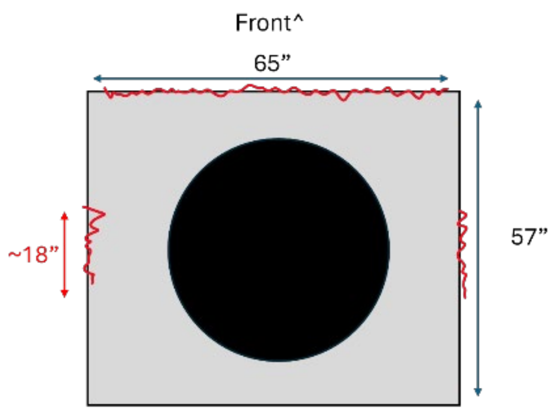
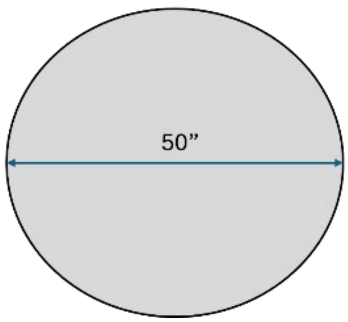


Figure D-7. Suspension.

- Area = NONE
- Holiday edge length testing 97 in (red line)
- Both sides and U cut-out in center

Figure D-8. Welds (front).





- Area = 1,741.5 in^2
- Holiday edge length testing 101 inches (red line)
- No holiday testing done on edge
- A = π (25 in)^2 = 1,963.5 in^2

Figure D-9. Roof and hatch (on roof).

- AREA = 480 IN^2
- Holiday edge length testing 96 inches (red line)

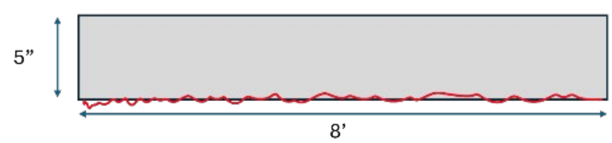


Figure D-10. Body panel (rear).

Figures D-11 to D-17 plot the distribution of DFT for the part assemblies. The data are segregated by part assemblies, showing some severe SoC (S.SoC) versus those with either no corrosion or only SoC1.

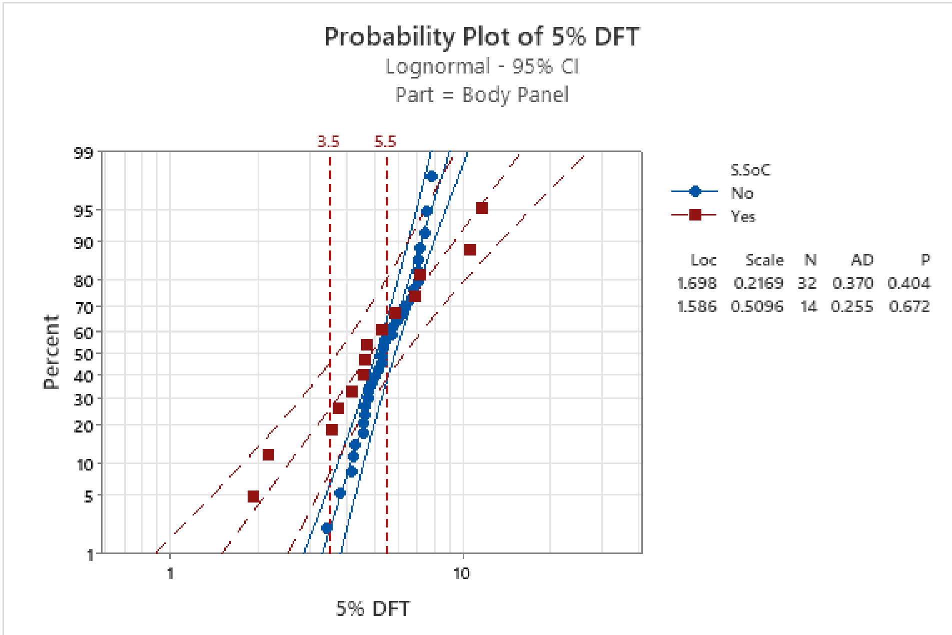


Figure D-11. Distribution of 5% DFT projection, parts with or without SoC, body panels.

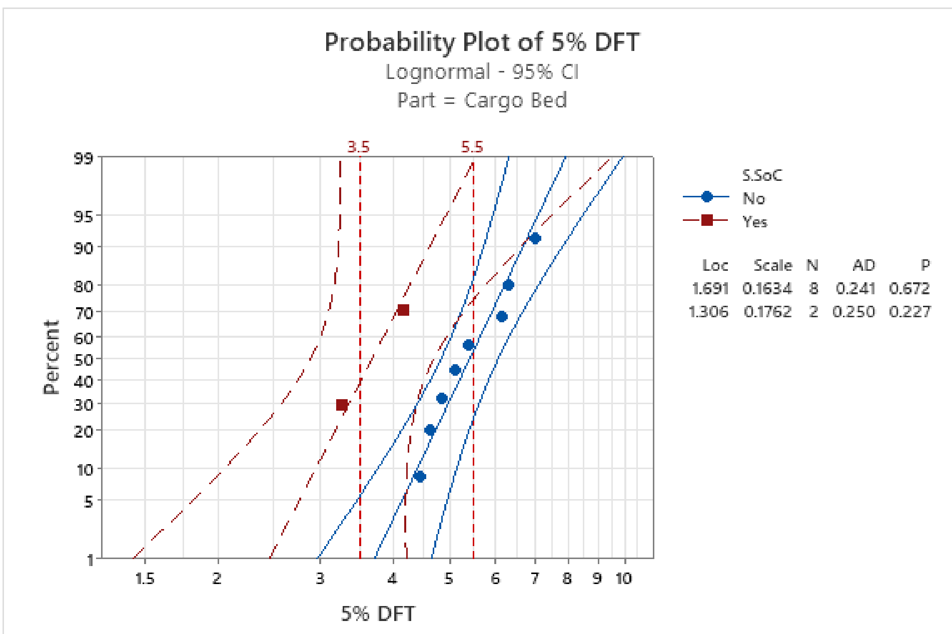


Figure D-12. Distribution of 5% DFT projection, parts with or without S.SoC, cargo bed.

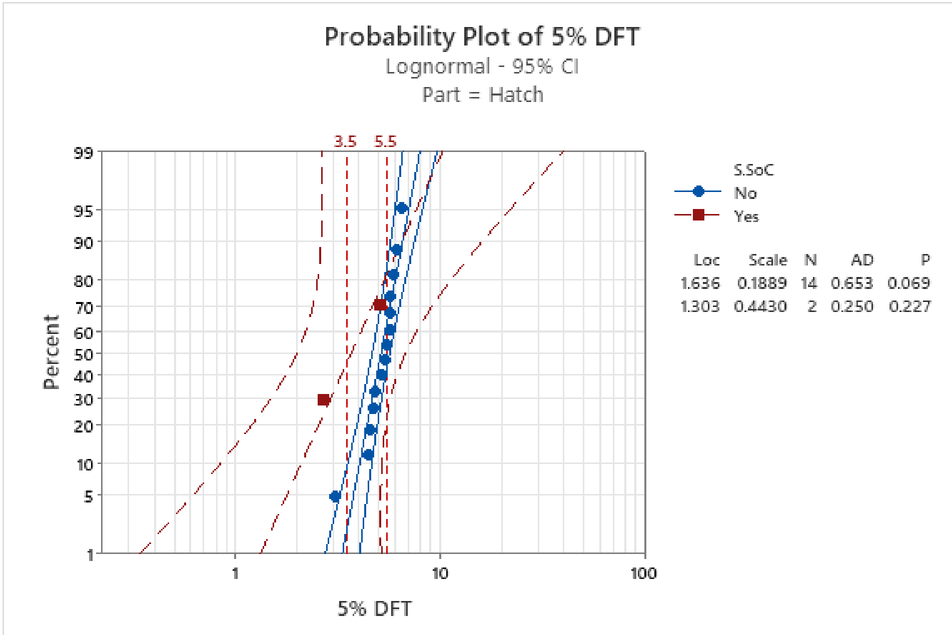


Figure D-13. Distribution of 5% DFT projection, parts with or without S.SoC, hatch.

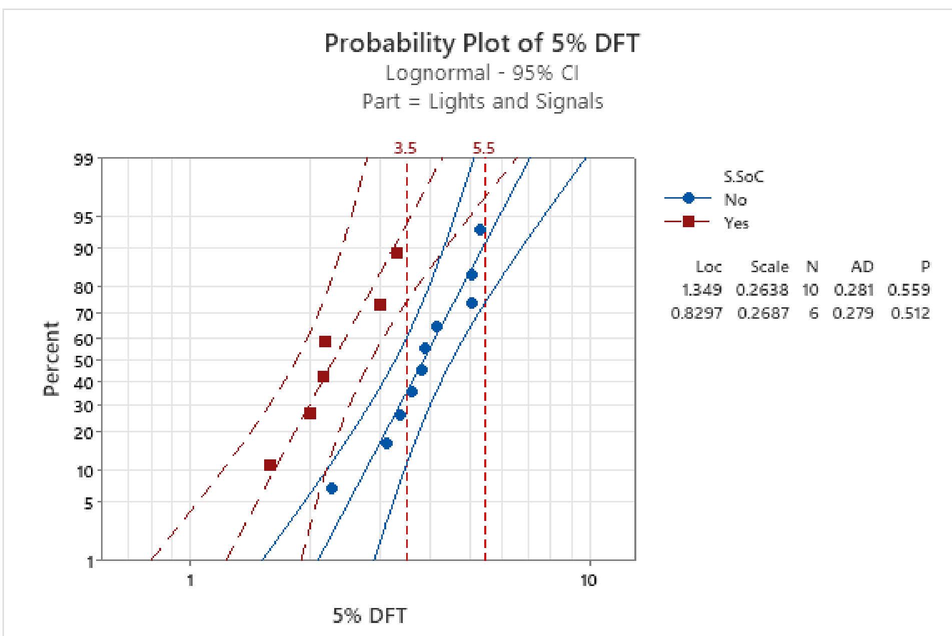


Figure D-14. Distribution of 5% DFT projection, parts with or without S.SoC, lights and signals.

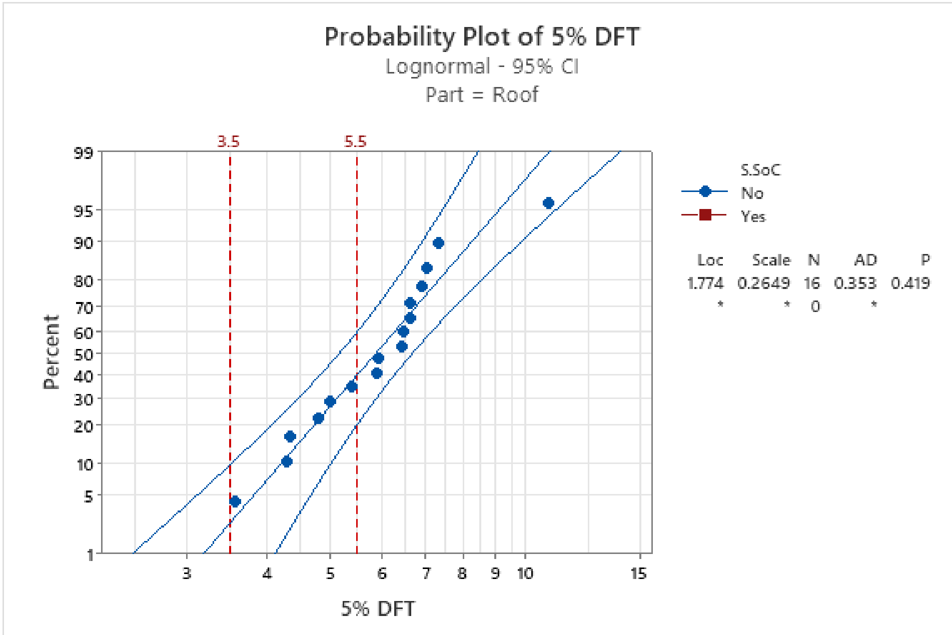


Figure D-15. Distribution of 5% DFT projection, parts with or without S.SoC, roof.

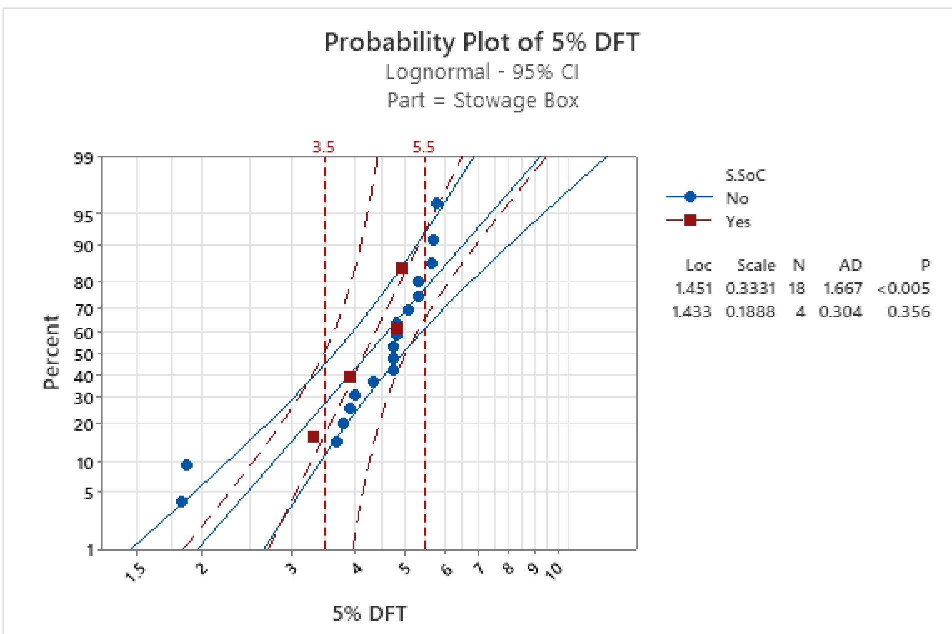


Figure D-16. Distribution of 5% DFT projection, parts with or without S.SoC, stowage box.

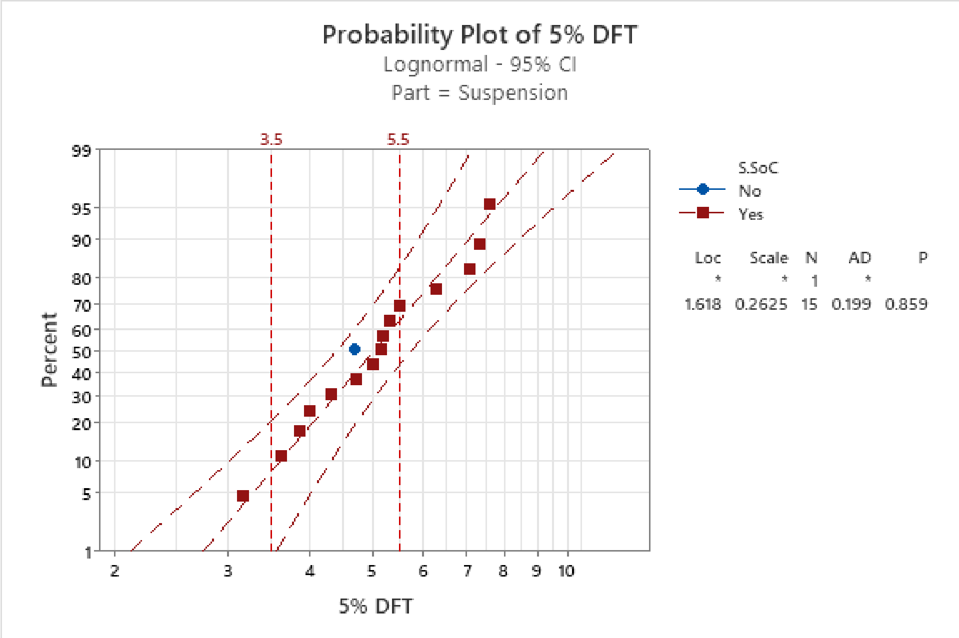


Figure D-17. Distribution of 5% DFT projection, parts with or without S.SoC, suspension.

Figures D-18 to D-28 summarize the distributions for holiday counts on the different areas inspected. Extreme value access is not a good fit for most of the data, yet it shows the diversity that can occur on fielded items.

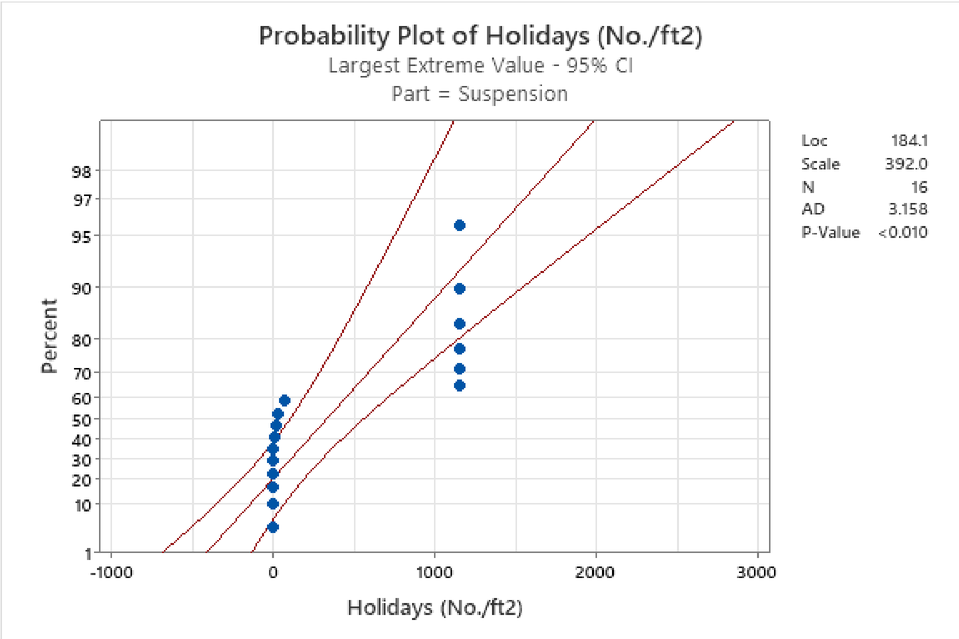


Figure D-18. Distribution of holiday density on "flat," suspension.

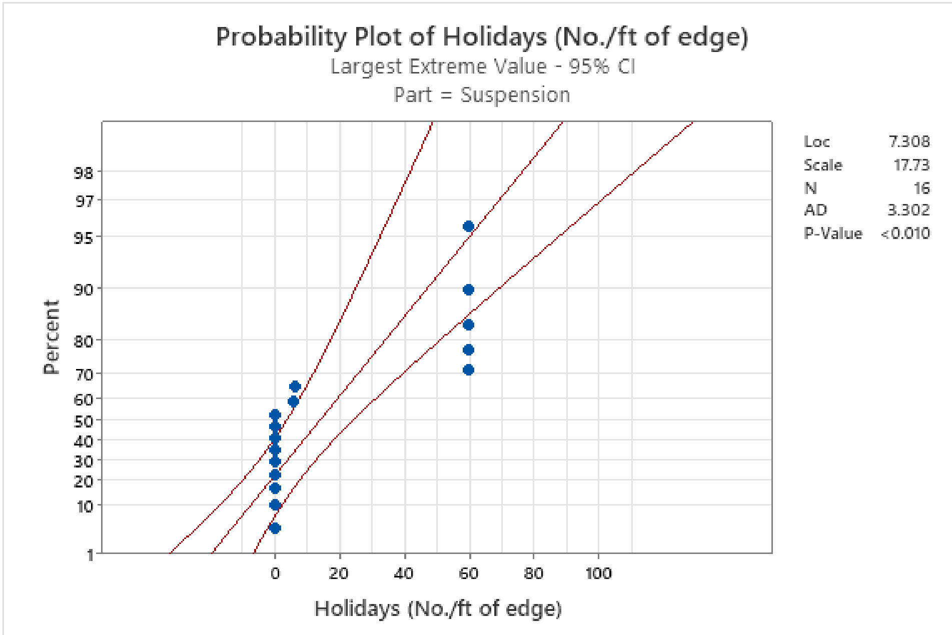


Figure D-19. Distribution of holiday density on edge, suspension.

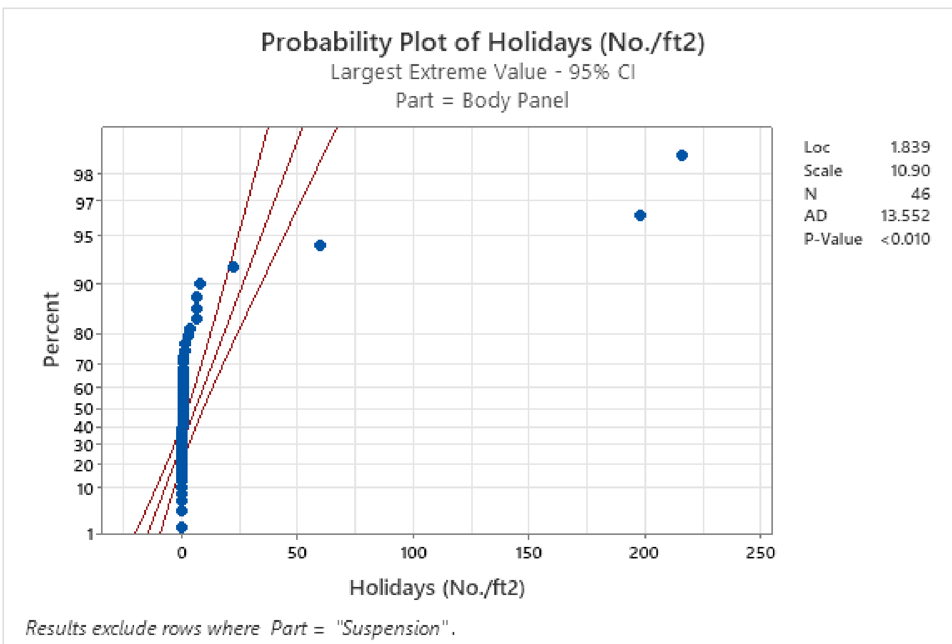


Figure D-20. Distribution of holiday density on flat, body panel.

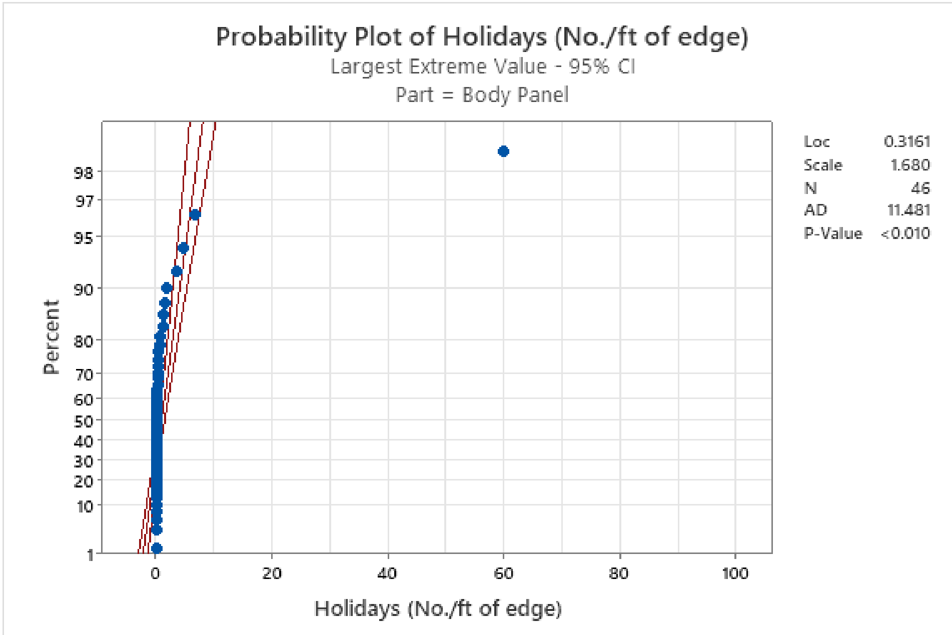


Figure D-21. Distribution of holiday density on edge, body panel.

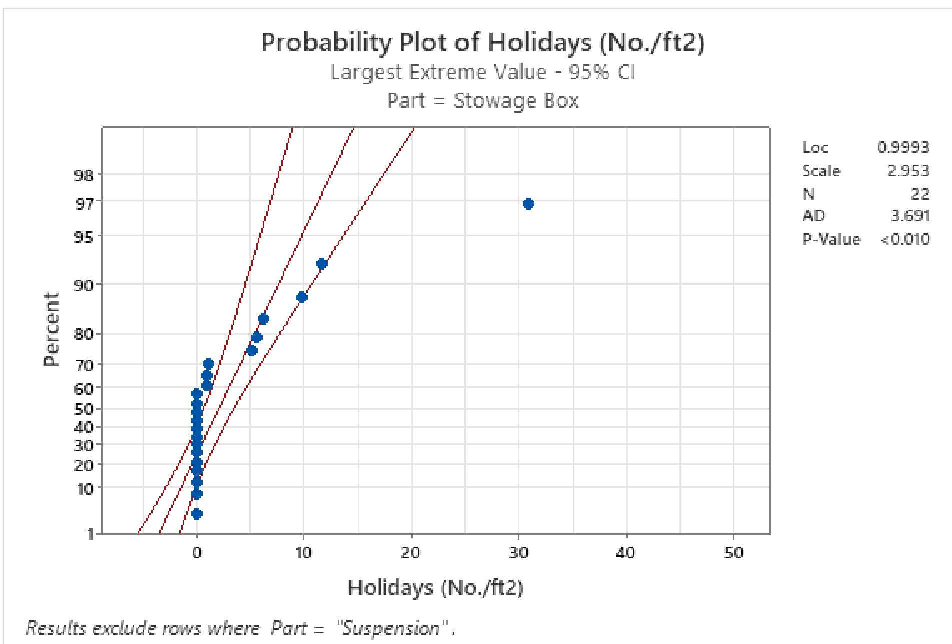


Figure D-22. Distribution of holiday density on flat, stowage boxes.

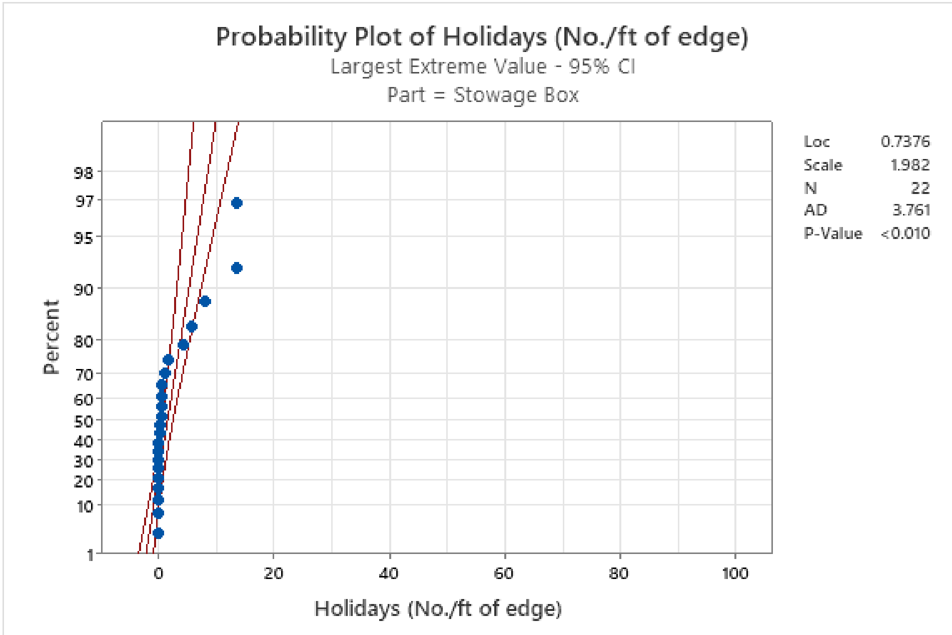


Figure D-23. Distribution of holiday density on edge, stowage boxes.

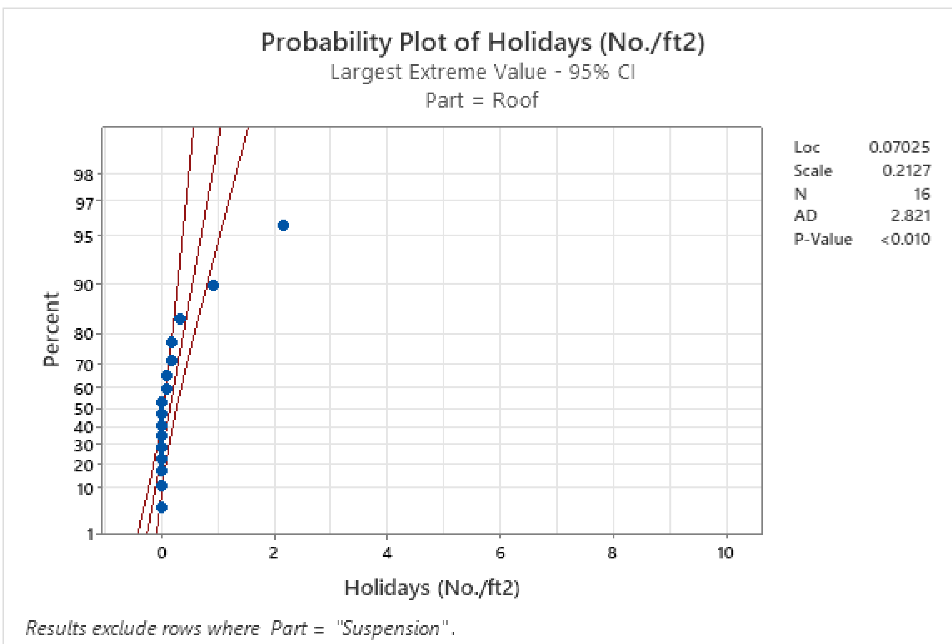


Figure D-24. Distribution of holiday density on flat, roof.

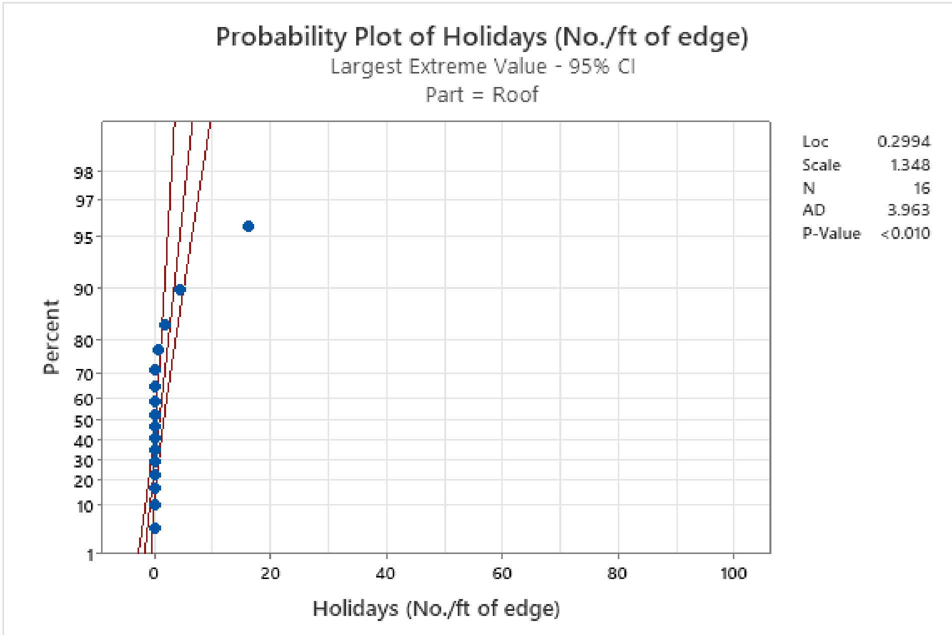


Figure D-25. Distribution of holiday density on edge, roof.

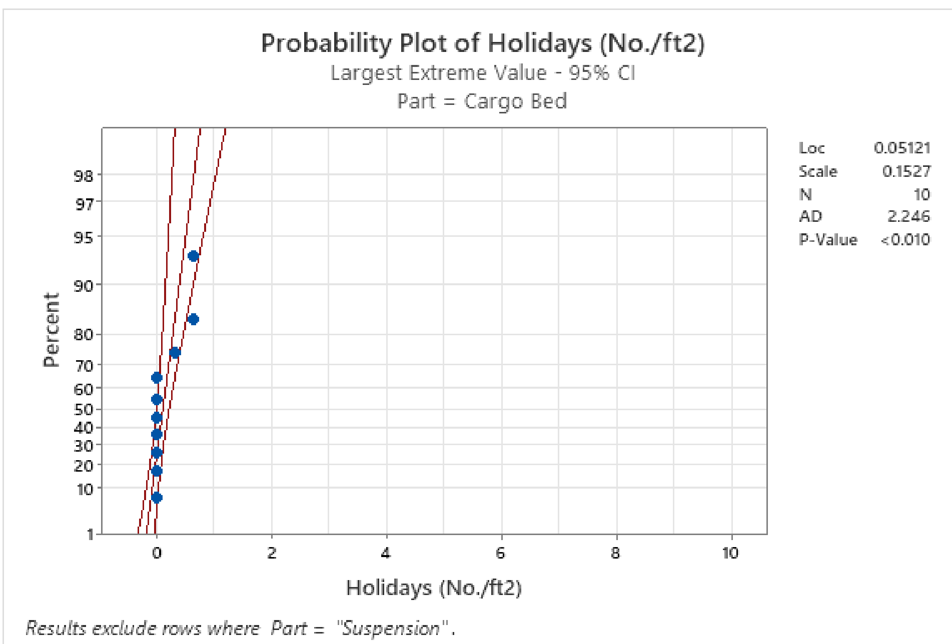


Figure D-26. Distribution of holiday density on flat, cargo bed.

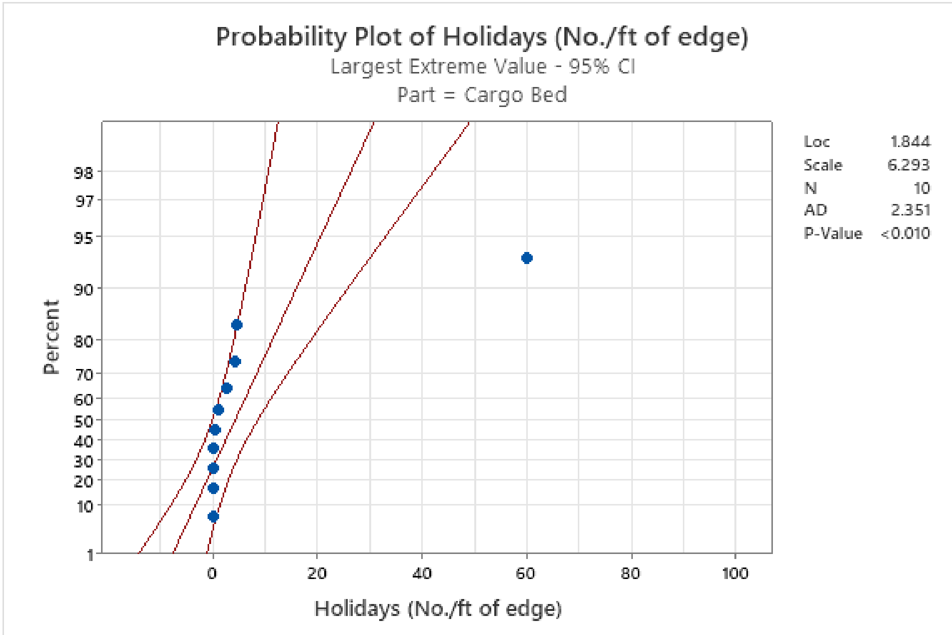


Figure D-27. Distribution of holiday density on edge, cargo bed.

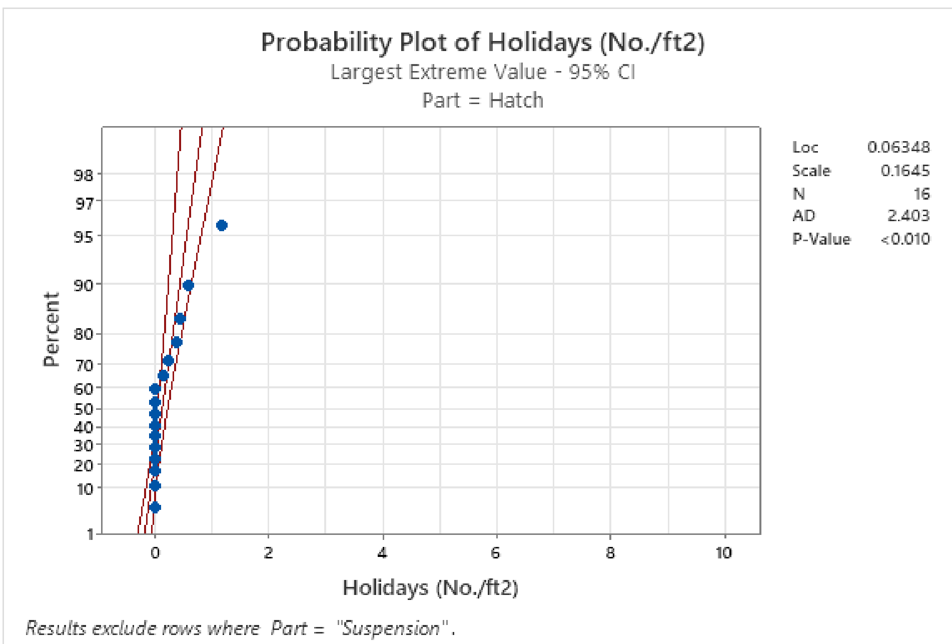


Figure D-28. Distribution of holiday density on flat, hatch.

Appendix E. Coating Defect Size and Proximity Effects Testing

Understanding that different initial defect types and densities would occur on ground system coatings, the program included a simple exposure study to examine the impacts of initial holiday size (i.e., diameter) and proximity to similar holidays (i.e., separation distance) on eventual creep. Japanese researchers reported that the size and proximity of paint coating defects affect the corrosion behavior.[1] In their work, cyclic corrosion tests were conducted on coated steel plates with both single and multiple adjacent circular defects to observe the progression of corrosion over time. The sizes of defects ranged from 1 to 20 mm in diameter, with different proximities between defects. In this study, we found that larger defects lead to greater mean and maximum corrosion, and multiple adjacent defects resulted in faster corrosion growth than a single defect, showing a combined corrosion effect. This research highlighted the importance of addressing multiple coating defects in corrosion prevention. Our project aimed to investigate the impact of defect size and proximity on the corrosion of substrates coated with specific Chemical Agent Resistant Coating (CARC) systems, with the goal of informing the design of a corrosion model.

E.1 Approach

To better inform the model, we designed a small test to determine the effect of defect size and proximity on corrosion and coating disbondment. We exposed them to three different environments and had three different panel configurations of proximity and defect sizes.

Two different types of coatings systems were evaluated. The first group included 3- × 5-inch carbon steel panels coated with CARC MIL-DTL-53084[2] E-coat[*] (1–2 mils target dry film thickness [DFT]) followed by the MIL-DTL-53039[3] urethane (2–4 mils target DFT). The second group comprised 4- × 6-inch steel panels coated with a CARC system consisting of MIL-PRF-32550[4] zinc-rich primer (2.5–3.5 mils target DFT), MIL-DTL-53022[5] (3–5 mils target DFT) epoxy primer, and MIL-DTL-53039[3] CARC topcoat (2–4 mils target DFT).

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[1] Kainuma S, Kobayashi J, Utsunomiya K, Sakamoto T. Influence of size and proximity of paint coating defects of corrosion behavior on carbon steel plates. J Jpn Soc Civ Eng. 2020;8:87–102.
[2] MIL-DTL-53084. Primer, cathodic electrodeposition, chemical agent resistant. Department of Defense (US); 2023.
[*] Applied by Almond Products, a PPG-recommended applicator, PPG Powercron CF-590-534, QPD-53084 E-coat product.
[3] MIL-DTL-53039. Camouflage coating, solvent based, chemical agent resistant. Department of Defense (US); 2022.
[4] MIL-PRF-32550. Metal-RICH PRIMER. Department of Defense (US); 2025.
[5] MIL-DTL-53022. Primer, epoxy coating, corrosion inhibiting lead and chromate free. Department of Defense (US); 2021 Apr 15.

There were three defect configurations of panels in the program. Panel configuration 1 (Figure E-1) contained three rows of single defects, each initially had a different size of circular defects (0.5, 1.0, and 3.0 mm) with the same proximity distance between defects in each row. Figure E-2 shows panel configuration 2, which had two defects per row. Each row had the same size of defects (1.0 mm) and different proximity distances (10, 20, and 30 mm). Figure E-3 shows panel configuration 3 with two initial defects per row, each set with 10-mm proximity distances. Each row had a different sized initial defect of 0.5, 1.0, and 3.0 mm.

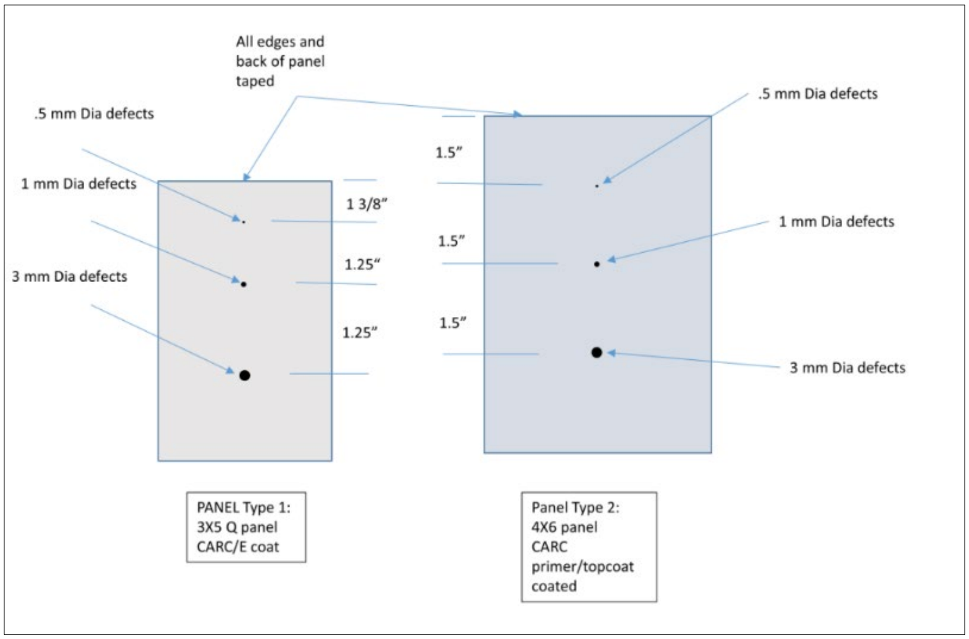

Figure E-1. Single-defect panel configuration.

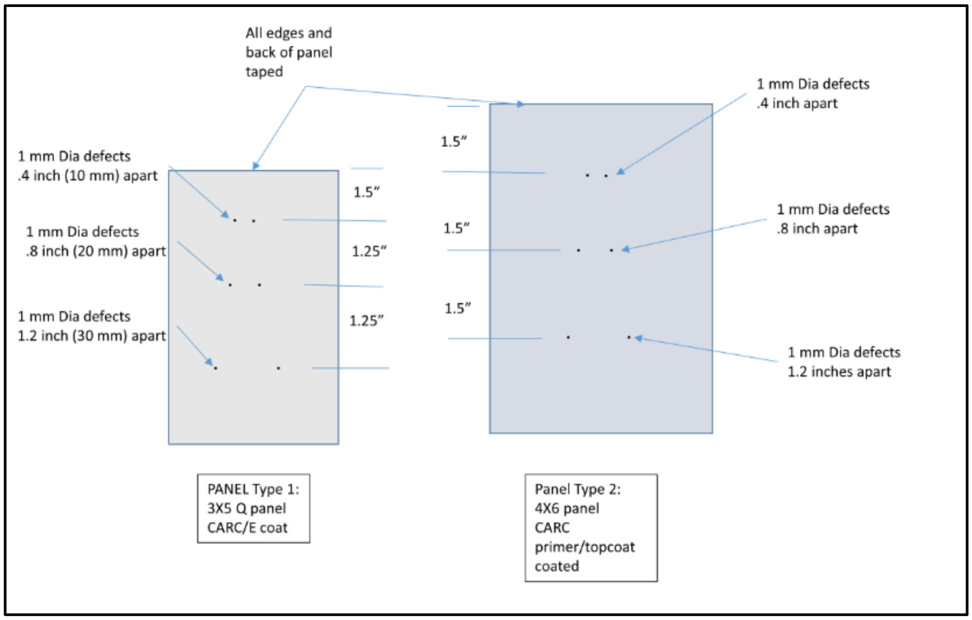

Figure E-2. Multiple defects per row, same diameter, multiple proximity distances panel configuration.

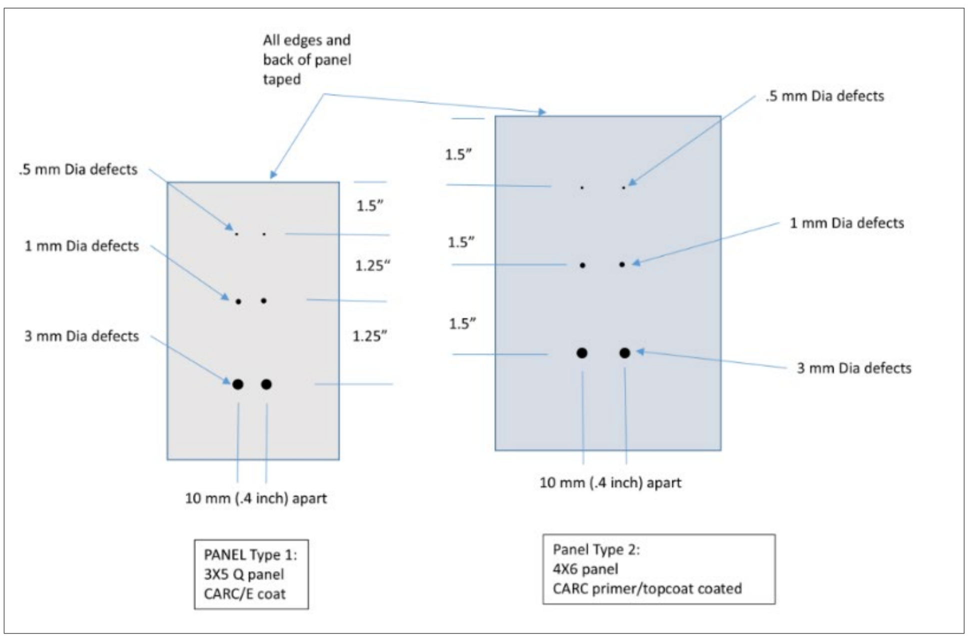

Figure E-3. Multiple defects per row, same proximity distance panel configuration.

Each panel DFT was measured and recorded. The panels were also tested for holidays before adding intentional defects. Those panels with unintentional holidays found in the coating were excluded from test. There was an attempt to divide up the panels so that the low and high DFT panels were divided among all groups as evenly as possible.

The defects were made in each panel, attached to a stand, using a Dremel with router bits. The smallest holes were made by hand to avoid breaking the bit. A template for each panel was created using a 3D printer and used to ensure standardized locations for the defects.

E.2 Exposure Environments

The panels were exposed to one of three environments:

1) Indoor accelerated testing (GMW14872[6])
2) Outdoor exposure at Vineland, New Jersey
3) Outdoor exposure at Vineland, New Jersey, plus daily salt spray

The indoor accelerated test panels were exposed in a cyclic corrosion cabinet in accordance with GMW14872.[7] They were taken out, rated and photographed every 5 cycles and were removed from test at 120 cycles.

Both sets of outdoor panels were exposed on the racks in Vineland, New Jersey, for up to 97 weeks. They have been inspected for corrosion at the defect and photographed periodically.

The defect creep was measured as the nominal diameter across the initial defect. Each panel was also evaluated overall for degree of corrosion using ASTM D610[7] and for degree of blistering using ASTM D714.[8]

E.3 Inspection Data

The data from natural exposure of panels with the zinc-rich primer showed relatively little, if any, creep after 97 weeks, even with the periodic seawater spray. Of the 108 holidays in the test panels, only 18 (17%) are showing minimal creep (Figure E-4). This demonstrates the high performance of the zinc-rich primer yet precludes significant understanding of initial holiday size and dispersion.

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6 GMW14872. Cyclic corrosion laboratory test. GWE Standards; 2021.
7 ASTM D610. Standard practice for evaluating degree of rusting on painted steel surfaces. ASTM International; 2019.
8 ASTM D714. Standard test method for evaluating degree of blistering of paints. ASTM International; 2017.

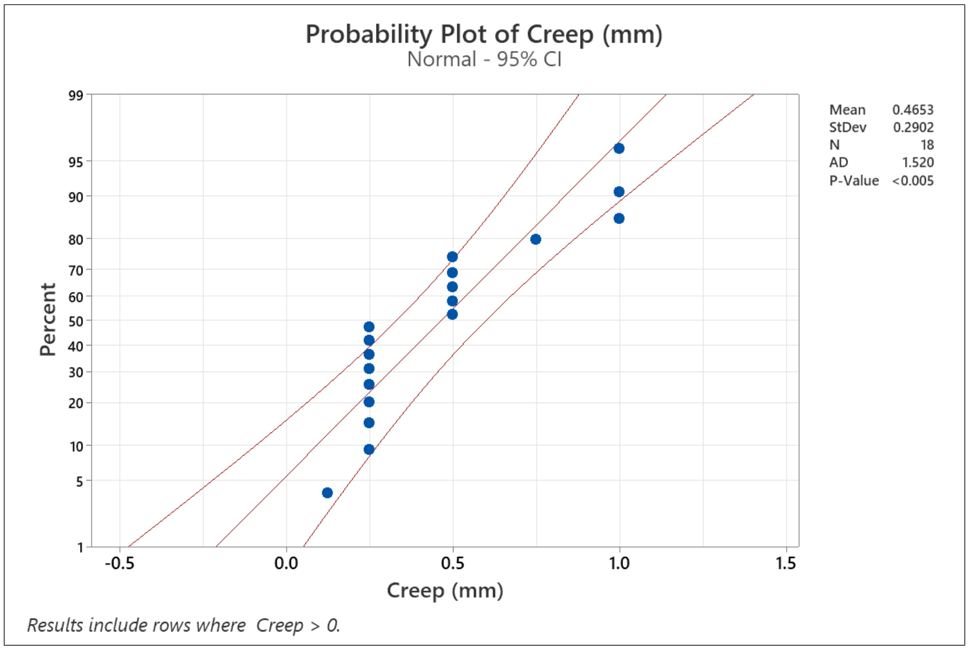


Figure E-4. Normal distribution of creep (mm).

Figure E-5 shows the effects of coating thickness, initial defect diameter, and separation distance of the defects on the diameter of the creep around the initial defect. The data show a strong influence of coating thickness on the observed creep. The ultimate observed diameter increases with the size of the initial defect; the increase in creep at 3.0 mm is more than 2.0 mm, or the difference in initial defect diameter from the 1.0-mm defects. The creep diameter seems to increase as the defects become closer to each other.

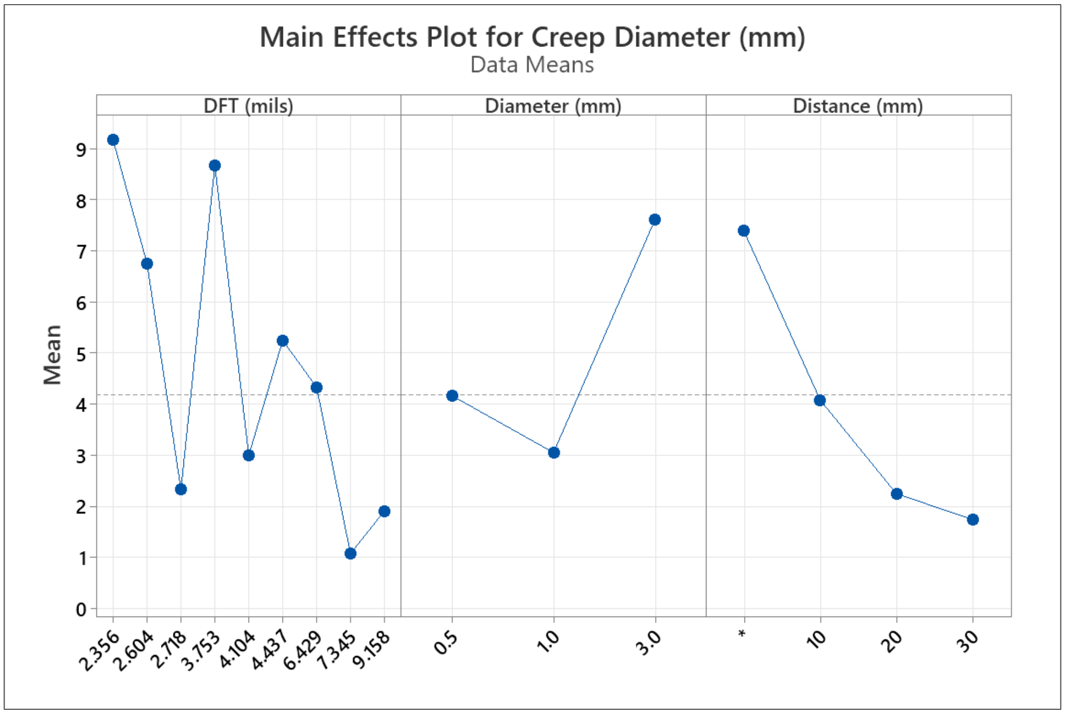


Figure E-5. Main effects of coating thickness, initial defect size, and defect separation on observed creep diameter for e-coat/53039 at 97 weeks, natural rural exposure.

The creep diameter was largest for the panels with a single holiday (see Table E-1, None-single holiday indications). This is probably associated with the slightly lower DFT average for those panels. Every attempt was made to include a similar range of DFT panels in each grouping. Table E-1 shows the average DFT of the panels in the datasets. The 20- and 30-mm separated defects were on the same panels, at different heights. The single-defect panels had a lower coating thickness that can be critical. The 10-mm separation panels had a higher creep diameter than the 20- and 30-mm separation panels, but they had the highest film thickness. This supports the significance of the separation distance on the observed corrosion growth from a defect.

Table E-1. Average and StDev in DFT (mils), segregated by panel defect separation, natural exposure.

Defect separation (mm)	Average DFT (mils)	DFT σ (mils)
None-single holiday	3.9	1.7
10	5.2	2.6
20	4.7	2.1
30	4.7	2.1

Figure E-6 and Table E-2 present the same data for the E-coat panels subjected to periodic seawater spray. The data suggests the same relationships as those for panels without the seawater spray. The overall magnitude of the creep diameter is just above 2 times greater than for the panels without the seawater spray.

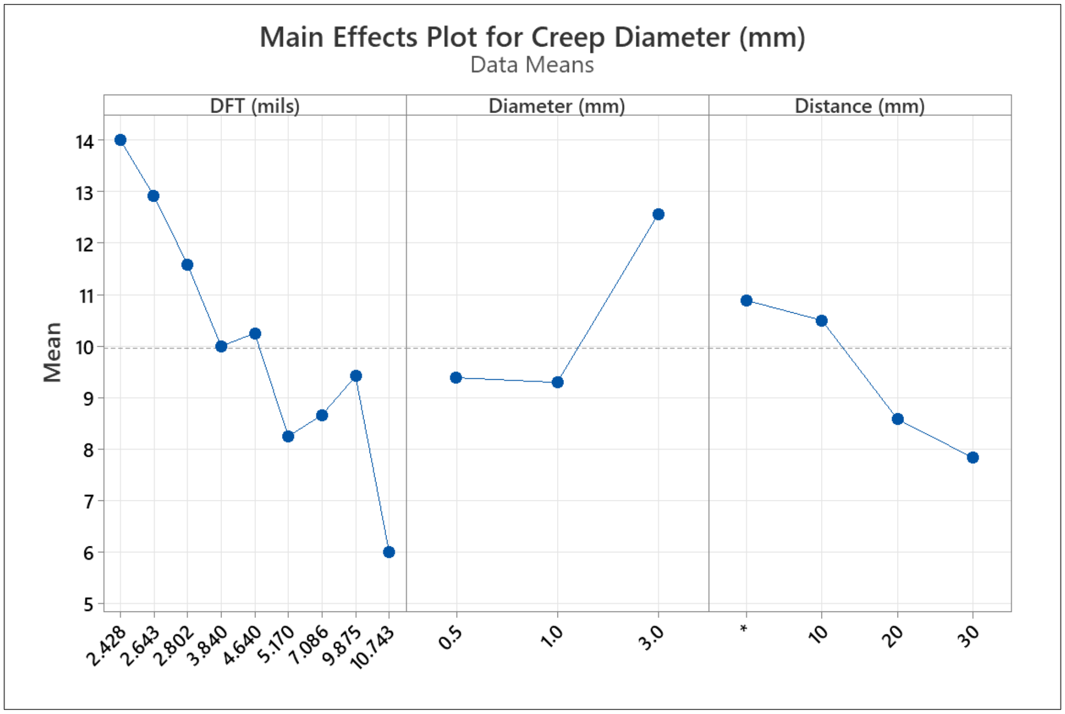


Figure E-6. Main effects of coating thickness, initial defect size, and defect separation on observed creep diameter for e-coat/53039 at 97 weeks, natural exposure with periodic seawater spray.

Table E-2. Average and StDev in DFT (mils), segregated by panel defect separation, panels with seawater spray.

Defect separation (mm)	Average DFT (mils)	DFT σ (mils)
None-single holiday	4.0	1.9
10	5.8	3.2
20	6.2	3.6
30	6.2	3.6

In accelerated testing, the results differ from those of natural exposure testing. Figures E-7 and E-8 summarize the results of the testing of the zinc-rich/epoxy/urethane CARC system (32550/53022/53039) and the e-coat/53039 coatings. Unlike natural exposure, in the accelerated testing the zinc-rich systems showed significant creepage at the defects. The creepage on the e-coat/53039 exceeded that of the zinc-rich coating in the same accelerated test environment. For both coatings, there is no consistent effect among increasing film thickness, and the relationship of creepage diameter to holiday separation is opposite of that in the natural environment. The high relative metallic corrosion rates observed in accelerated testing may tend to overwhelm the factors that control creepage in a natural environment.

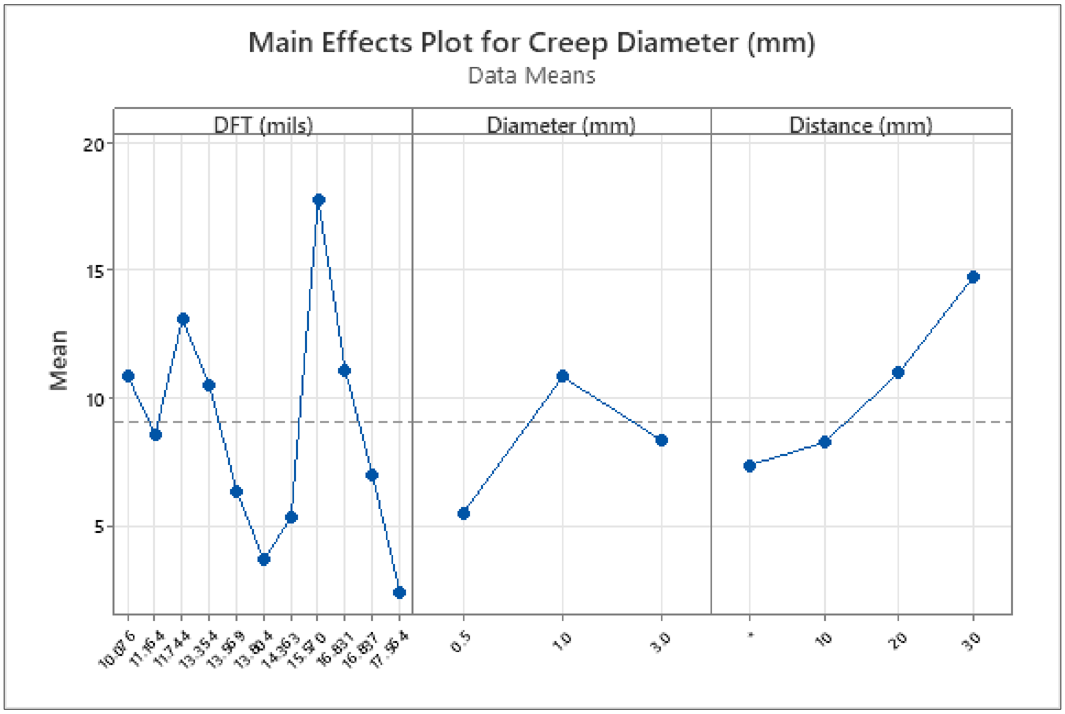


Figure E-7. Main effects of coating thickness, initial defect size, and defect separation on observed creep diameter for 32550/53022/53039 coating at 140 cycles GMW14872.[7]

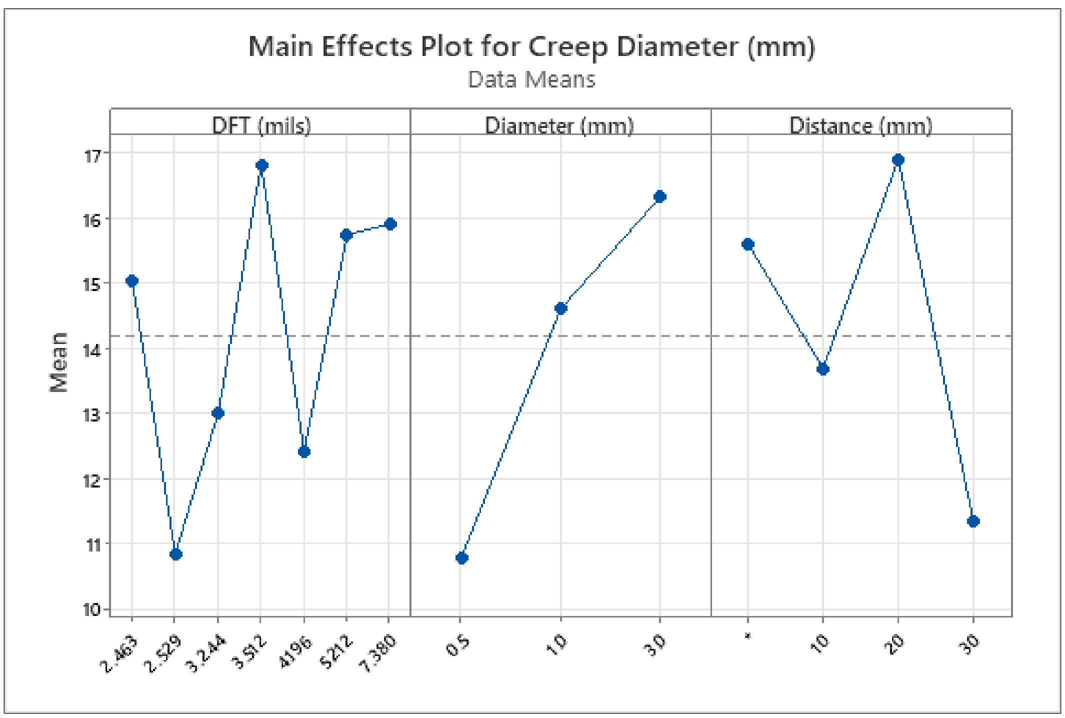
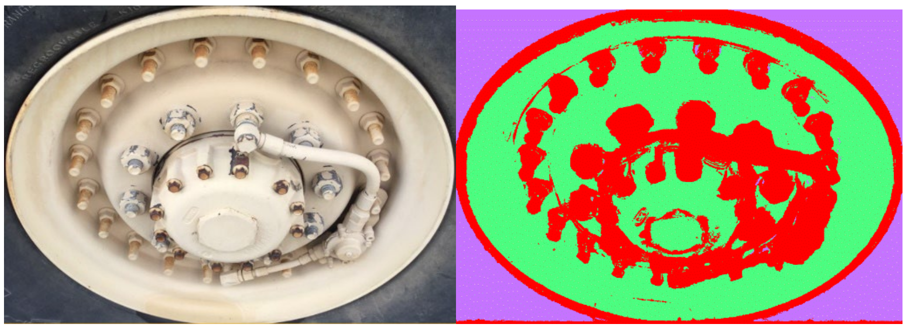


Figure E-8. Main effects of coating thickness, initial defect size, and defect separation on observed creep diameter for e-coat/53039 at 140 cycles of GMW14872[7] testing.

Appendix F. Edge-to-Surface Area Ratio Estimates

We determined the Edge-to-Flat surface area ratio by using a combination of ImageJ analysis and visual analysis. We started by using ImageJ software to analyze several photos of each assembly type (Figures F-1 to F-3). The images were segmented utilizing the ImageJ software to select edges and complex areas in one color and flat areas with no complexities in another. Any background was selected in another distinct color. The results were analyzed to determine the ratio of the complex area to the noncomplex area using ratio of colors and provided a complexity ratio (complex/nocomplex). Several photos of each assembly type were analyzed, and the average determined.



(purple = background, red = complex features, green = flat areas).

Figure F-1. ImageJ analysis of wheels and lugs.

(red = background, green = complex features, purple = flat areas).

Figure F-2. ImageJ analysis of connection point.

(red = background, green = complex features, purple = flat areas).

Figure F-3. ImageJ analysis of one type of bracket.

Given the variation in each part, the initial ratio was paired with human subject matter expert (SME) opinions from inspecting and visually analyzing actual parts and all the photos in the database for each assembly. In the final data, we found that most of the area was considered flat or of low complexity. The complex areas were further divided into medium and high complexity categories based on SME opinion and discussion. Generally, those part assemblies with closely located complex features were judged to be more of "high" complexity (wheels and lugs, latches, etc.) versus "medium" complexity (door frames, seats, etc.). Table F-1 summarizes the results of these analyses.

Table F-1. Summary of the Conditional Probability Table for part assembly edge-to-surface area ratio.

Part assembly	**Edge-to-surface area ratio**		
	Low	**Medium**	**High**
Wheels and Lugs	25	25	50
Connection Points	70	20	10
Brackets	20	30	50
Fasteners	5	5	90
Suspension	70	10	20
Drivetrain	70	20	10
Bumper	70	25	5
Steps	85	10	5
Hydraulic and Air Lines and Connections	50	30	20
Mirrors	60	25	15
Lights and Signals	70	15	15
Hinges	60	25	15
Body Panels	80	15	5
Cargo Bed	80	15	5
Flooring	95	4	1
Frame	65	25	10
Door Frame	80	15	5
Spare Tire Mount	80	15	5
Roof	95	4	1
Hydraulic and Air Systems	50	30	20
Pedals	80	15	5
Dashboard	80	15	5
Seats	80	15	5
Latches	5	5	90
Stowage Boxes	80	15	5
Ladder	80	15	5
Electrical Connectors and Components	50	30	20
Handles	80	15	5
Truck Bed	80	15	5
Exhaust	80	15	5
Turret Ring	70	25	5
Welds	65	30	5

Appendix G. Linking Corrosion Among Part Groups

In Appendix G, we discuss the link between various part groups. Specifically, there is a relationship between the corrosion observed on the most visible parts, such as fastener corrosion or other Group 1 parts, and the remaining part assemblies.

To evaluate this potential, the effort focused on the 32-part assemblies, divided into eight part-groups with four members each (Table G-1). Table G-1 shows these part assemblies and the probability that an asset would show one or more of these part assemblies with a Severe Stage of Corrosion (S.SoC).

Table G-1. Percentage of assets showing an S.SoC for one or more key part assemblies.

Group1		Group5	
WHEELS AND LUGS	47%	DOOR FRAME	3%
CONNECTION POINTS	52%	SPARE TIRE MOUNT	3%
BRACKETS	32%	ROOF	3%
FASTENERS	28%	HYDRAULIC AND AIR SYSTEMS	5%
Group2		**Group6**	
SUSPENSION	29%	PEDALS	3%
DRIVETRAIN	28%	DASHBOARD	2%
BUMPER	22%	SEATS	7%
STEPS	13%	LATCHES	5%
Group3		**Group7**	
HYDRAULIC AND AIR LINES AND CONNECTIONS	17%	STOWAGE BOXES	4%
MIRRORS	12%	LADDER	6%
LIGHTS AND SIGNALS	17%	ELECTRICAL CONNECTORS AND COMPONENTS	3%
HINGES	3%	HANDLES	6%
Group4		**Group8**	
BODY PANELS	8%	TRUCK BED	2%
CARGO BED	9%	EXHAUST	5%
FLOORING	5%	TURRET RING	3%
FRAME	6%	WELDS	2%

Table G-2 summarizes the corrosion patterns observed for each part grouping for all 2,125 assets. The pattern is presented as a four-bit number with each digit "1" representing a finding of S.SoC on the corresponding part within that group. Table G-3 shows an example of how the digit placement represents an S.SoC on that part assembly.

Table G-2. Pattern of part assemblies with S.SoC.

S.SoC pattern	Pattern count per individual group							
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1111	269	46	4	1	0	1	0	0
1110	202	95	31	4	1	0	2	2
1101	134	30	3	8	0	0	3	0
1011	20	41	5	5	0	0	0	0
0111	40	22	3	3	1	1	2	1
1100	195	156	54	34	0	4	6	12
1010	36	71	67	19	4	4	9	0
1001	31	28	11	18	6	5	6	2
0110	49	48	60	6	6	13	7	10
0101	38	18	6	18	7	5	18	8
0011	9	38	11	10	3	17	8	0
1000	104	159	179	90	46	49	61	30
0100	168	189	94	124	53	28	99	80
0010	50	102	189	61	39	113	42	46
0001	58	49	21	75	85	71	82	31
0000	722	1033	1387	1649	1874	1814	1780	1903

Table G-3. Pattern of part assemblies in Group 1 with S.SoC.

S.SoC pattern	Group 1			
	Wheels and lugs	Connection points	Brackets	Fasteners
1111	S.SoC	S.SoC	S.SoC	S.SoC
1110	S.SoC	S.SoC	S.SoC	None
1100	S.SoC	S.SoC	None	None
1010	S.SoC	None	S.SoC	None
1000	S.SoC	None	None	None
0001	None	None	None	S.SoC
0000	None	None	None	None

The results in Tables G-2 and G-3 can be compared with the expected count based on chance. Because the individual probabilties of the part assemblies that have an S.SoC are known (Table G-1), the probabilties of combinations of these parts, either with or without an S.SoC, can be derived via joint probabilties. The ratio of the actual part count to the count expected by chance is shown in Table G-4. There is a higher ratio versus chance at the higher incidences of common corrosion across multiple parts.

Table G-4. Ratio, actual to chance, part assemblies with SoC.

Pattern	Ratio, actual to chance							
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1111	5.8	9.2	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*
1110	1.7	2.8	4.4	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*
1101	1.4	1.7	3.0	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*
1011	0.5	3.4	2.5	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*
0111	0.8	1.8	3.0	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*	NO OBSRV*
s1100	0.8	1.3	1.6	2.3	. . .	4.0	1.2	6.0
1010	0.3	0.8	1.3	2.4	4.0	1.0	3.0	. . .
1001	0.3	0.6	1.4	1.8	2.0	1.7	1.5	2.0
0110	0.4	0.6	1.7	0.7	3.0	4.3	1.8	3.3
0101	0.3	0.4	1.2	1.6	2.3	2.5	2.6	4.0
0011	0.2	1.3	1.4	1.7	1.5	2.4	2.0	. . .
1000	0.4	0.5	0.7	0.6	0.9	0.9	0.8	0.7
0100	0.6	0.6	0.6	0.8	0.9	0.6	0.8	0.8
0010	0.4	0.5	0.7	0.7	0.8	0.8	0.7	0.9
0001	0.5	0.5	0.5	0.7	0.9	0.8	0.8	0.8
0000	2.7	1.4	1.1	1.1	1.0	1.0	1.0	1.0

Note: NO OBSRV* = This pattern was not observed in the dataset.

Table G-4 shows that there are concentrations of behavior wherein parts groupings are more or less corroded than would be expected by chance. This suggests that there are common factors driving this behavior. Given that coating quality and part complexity would be expected to be somewhat randomly distributed across the platform, a logical assumption would be a common factor of "use."

Table G-5 takes the analysis one step further to show the relationship between the Group 1 and Group 2 parts. Data are assembled for each possible count of the parts in Group 1 that show an S.SoC. These values range from 0 to 4, because there are four parts in this group. Table G-5 shows the expected percentage of parts within Group 2, which might also have 0 to 4 corroded items. The data show that as the number of severely corroded parts in Group 1 decrease, there is a comensurate shift in the Group 2 distribution toward a lower number of severely corroded parts.

Table G-5. Relationship between corrosion in Group 1 vs. Group 2.

Group 1: S.SoC part count (any pattern)	Group 2: S.SoC part count (any pattern)				
	4 S.SoC parts	3 S.SoC parts	2 S.SoC parts	1 S.SoC part	0 S.SoC parts
4 (269 OBSRV)	11%	33%	33%	18%	4%
3 (396 OBSRV)	4%	18%	33%	29%	16%
2 (358 OBSRV)	1%	6%	20%	40%	33%
1 (380 OBSRV)	0%	0%	11%	27%	61%
0 (722 OBSRV)	0%	0%	3%	12%	84%

Note: OBSRV = This pattern was observed in the dataset.

List of Symbols, Abbreviations, and Acronyms

3D	Three-Dimensional
ARL	Army Research Laboratory
ASTM	American Society for Testing and Materials
BBN	Bayesian Belief Network
BN	Bayesian Network
CARC	Chemical Agent Resistant Coating
CCSFS	Cape Canaveral Space Force Station
CIC	Corrosion Inhibiting Compound
CPC	Corrosion Prevention and Control
CPT	Conditional Probability Table
DEVCOM	U.S. Army Combat Capabilities Development Command
DFT	Dry Film Thickness
DoM	Date of Manufacture
FMTV	Family of Medium Tactical Vehicles
GVSC	Ground Vehicle Systems Center
HIGH	Areas with DFT Higher Than the Specified Range
HMMWV	High Mobility Multipurpose Wheeled Vehicle
ID	Identification
LMTV	Light Medium Tactical Vehicle
LOW	Areas with DFT Lower Than the Specified Range
NA	Not Applicable
NoCorr	No Corrosion
NSN	National Stock Number
PRM	Probabilistic Relationship Model
SME	Subject Matter Expert
SoC	Stage(s) of Corrosion Rating

SoC1/2/3/4	Stage of Corrosion 1/2/3/4 Rating
SoC3+	SoC3 and SoC4
SPEC	Areas with DFT within the Specified Range
S.SoC	Severe Stage(s) of Corrosion
StdDev	Standard Deviation
TACOM	U.S. Army Tank-Automotive and Armaments Command
TOW	Time of Wetness

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