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THESIS

CORROSION PROTECTION IN THE DESERT

by

Robert L. Turner

September 2022

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13. ABSTRACT (maximum 200 words)

From November 2021 to May 2022, a corrosion-prevention experiment was conducted at the Marine Corps base in Twentynine Palms, California. The experiment consisted of 21 bare steel coupons exposed to the desert environment and 30 bare steel coupons subjected to accelerated testing. Of the 21 test coupons, three were left untreated to act as a control group, six were coated with CorrosionX, six were coated with Carwell CP-90, and six were coated with Fluid Film. Of the 30 test coupons subjected to accelerated aging, 10 were coated with CorrosionX, 10 were coated with Carwell CP 90, and 10 were coated with Fluid Film. After the experiment was finished, the test coupons were analyzed by the analysis of variance statistical method. The results of the test suggested CorrosionX or Fluid Film was effective in slowing corrosion. Due to a small sample size, a relatively short experimental period, and unusual weather, however, further testing is recommended.

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CORROSION PROTECTION IN THE DESERT

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Submitted in partial fulfillment of the
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ABSTRACT

From November 2021 to May 2022, a corrosion-prevention experiment was conducted at the Marine Corps base in Twentynine Palms, California. The experiment consisted of 21 bare steel coupons exposed to the desert environment and 30 bare steel coupons subjected to accelerated testing. Of the 21 test coupons, three were left untreated to act as a control group, six were coated with CorrosionX, six were coated with Carwell CP-90, and six were coated with Fluid Film. Of the 30 test coupons subjected to accelerated aging, 10 were coated with CorrosionX, 10 were coated with Carwell CP 90, and 10 were coated with Fluid Film. After the experiment was finished, the test coupons were analyzed by the analysis of variance statistical method. The results of the test suggested CorrosionX or Fluid Film was effective in slowing corrosion. Due to a small sample size, a relatively short experimental period, and unusual weather, however, further testing is recommended.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	analysis of variance
CARC	chemical attack resistant coating
CED	Construction Equipment Division
CPC	corrosion prevention compounds
DOD	Department of Defense
°C	degrees Celsius
EXWC	Engineering and Expeditionary Warfare Center
FTFC	fluid thin film coating
NAVFAC	Naval Facilities Engineering Systems Command
NECC-PAC	Naval Expeditionary Combatant Command — Pacific
NRL	Naval Research Laboratory
TYCOM	type command
UV	ultraviolet light
WARTEC	western area research and technology evaluation center

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EXECUTIVE SUMMARY

Maintenance is a pressing issue for the U.S. Navy and corrosion control is an important component of that maintenance. Corrosion forces the Department of Defense to divert funds, negatively affects readiness, and detracts military personnel from their primary mission.

The U.S. Navy is arguably the most affected as most of its equipment is stationed near water out of necessity. Although ships receive the majority of the U.S. Navy's corrosion- related attention, other equipment, such as construction equipment, is also negatively affected. Construction equipment suffers sufficiently from the corrosion that the Navy Expeditionary Combatant Command-Pacific, the type command in charge of the construction equipment, considered stationing the equipment in the desert to help control corrosion.

Although corrosion in moist environments has been studied extensively, very little is known about corrosion in the desert. This study sought to improve the body of knowledge by conducting an experiment in corrosion control in a desert environment.

One potential way to prevent corrosion is to coat the metal with commercial-off-the-shelf corrosion-prevention compounds. These corrosion-prevention compounds were the focus of the experiment. Three corrosion prevention compounds were selected for the experiment: Carwell CP-90, CorrosionX, and Fluid Film. The compounds were selected either for their performance in previous experiments or by a recommendation from a corrosion officer. The goal of the experiment was to determine if one or more of the corrosion-prevention compounds would slow the rate of corrosion in the desert.

The experiment consisted of 21 low- grade steel test coupons, thoroughly cleaned, coated with three different corrosion preventive compounds, weighed, tied to a wooden pallet with zip ties, placed at a 30-degree angle to the sun, left exposed to the desert environment, cleaned with an ultrasonic cleaner and weighed again. The difference between the starting weight and the finishing weight was used to determine how much material was lost to corrosion. The weight loss was examined by the statistical technique analysis of variance to determine if there was a statistically meaningful difference in the weight loss to determine if one of the corrosion-prevention compounds worked better than the others.

Three of the test coupons were left untreated to act as a control, six were coated with CorrosionX, six were coated with Carwell CP-90 and six were coated with Fluid Film. The test coupons were placed in the western area research test and evaluation center at the Marine Corps Air Combat Center in 29 Palms, California. The western area research test and evaluation center was selected because it has a fenced-in area where the test coupons could be left undisturbed.

In addition to the field test, an additional 30 test coupons were also subjected to accelerated ageing in the laboratory. Accelerated ageing provided two benefits to the experiment: it provided a comparison of field results to a controlled laboratory conditions and it allowed testers to gather data on long term corrosion in a short time frame. Ten of the test coupons were coated with CorrosionX, 10 were coated with Fluid Film, 10 were coated with Carwell CP-90 and the test coupons were placed in an accelerated weather tester set at 113 degrees Fahrenheit. The test coupons were exposed for approximately one week of test time.

CorrosionX and Fluid Film performed better than the control group in some statistical analysis and that difference is statistically significant at the 0.05 level of significance. However, not all of the statistical analysis agreed with this decision, probably because the sample size was small, and the experimental period was relatively short.

There are sufficient questions remaining to suggest that a wise course of action would be to run the experiment again with a larger sample size and for a longer duration. Recommended is a one-year experiment with a sample size of 180 test coupons, consisting of 45 coated with CorrosionX, 45 coated with Fluid Film, 45 coated with Carwell CP-90 and 45 left untreated to serve as a control group.

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I. INTRODUCTION

A. MOTIVATION

Corrosion is a serious issue that costs the U.S. Navy 7 billion dollars a year (Husband 2014) and the Department of Defense (DOD) over nineteen billion dollars every year (Spadafora n.d.). Naval assets stationed on or near shore, are particularly vulnerable to corrosion. Any equipment staged near shore or deployed at sea is exposed to a marine environment that will exacerbate corrosion rates compared to inland conditions. The corrosion problem is worse on ships, but construction equipment based on land is not immune to corrosion. Ships and the aircraft stationed on them are in coastal waters out of necessity and cannot be relocated, but other equipment, such as construction equipment, can be moved inland.

Corrosion is negatively impacting the Naval Construction Force's equipment to the extent that the Naval Expeditionary Combatant Command-Pacific (NECC-PAC) considered permanently stationing the vehicles in the Mojave Desert of southern California (Steven Baker, discussion with the author, June 2019). The equipment is currently stored at Naval Base Ventura County, primarily at Port Hueneme, but also in Guam and Okinawa, Japan.

The Navy has studied corrosion extensively in coastal environments; however, very little is known about corrosion in other climates, such as in deserts. Sandia National Laboratories conducted research on desert corrosion in 1981, but they focused their research on alloy 800, an iron-nickel-chromium alloy used in solar panels (Hughes 1981). Work has also been done on corrosion affecting underground pipes, aircraft, and aluminum, but research on metal corrosion in the desert is lacking. How a desert environment affects the rates of corrosion in the steel alloys commonly used on NECC-PAC equipment is unknown.

Although NECC-PAC has considered coating vulnerable metal surfaces with corrosion prevention compounds, it is unknown for how long these would provide sufficient protection when exposed to the conditions of a desert (e.g., UV, extreme temperature fluctuations, from sandblasting from silicates in the wind). The goal of this thesis is to elucidate the efficacy of treating steel with these coatings. The results of this work will contribute to the body of knowledge of metal corrosion in desert environments, which can then inform commands like NECC-PAC in choosing equipment storage locations.

B. BACKGROUND

At the systems command level, maintenance for construction equipment falls under the Naval Facilities Engineering Systems Command (NAVFAC) Engineering and Expeditionary Warfare Center's (EXWC) Construction Equipment Division (CED). The former division director of the CED reported that he had seen about a dozen vehicles with fewer than 100 miles on the odometer rendered useless by corrosion (Joseph Parish, discussion with the author, June 2019). Vehicles with severe corrosion must be sent to depots for refurbishment. This is not only expensive, but it also affects readiness by taking the equipment out of service and ties up specialists who otherwise would be working to repair broken equipment.

There are solutions to the problem of corrosion, but these solutions do not come without a cost. One solution is to place the construction vehicles inside climate-controlled warehouses, but a previous study done by EXWC determined that the total cost of building and operating a climate-controlled warehouse capable of storing 250 units of construction equipment will cost an estimated $67.58 million dollars over ten years (Arias et al. 2021).

A second solution is to cover the vehicles with tarps. The construction equipment is large, however, and requires expensive, custom-built tarps, costing an estimated 800 dollars apiece (Arias et al. 2021). The Marine Corps used tarps to protect its vehicles at Marine Corps Logistics Base, Barstow, and their experience was the tarps will only last roughly one year before the environmental conditions render them useless and they must be replaced (Neal Pinchevsky, discussion with the author, May 2019).

Another solution is to regularly wash the vehicles, but this is manpower intensive, taking sailors away from their primary mission of training for war. Additionally, special wash racks are required to prevent environmental damage caused by runoff of petroleum, oil, and lubricants. The cost of these wash racks can exceed one million dollars (Joseph Parish, discussion with the author, June 2019) and water use in a desert environment is a significant environmental and financial concern.

There are corrosion prevention compounds (CPC) that can be applied to protect the metal. These CPCs are the focus of this report. Previous experiments showed the compounds are effective in a coastal environment (Arias et al. 2021), but it is unknown if the compounds are effective in the desert. Of particular concern is that the compounds may not survive the sandblasting effect caused by harsh desert winds. There is also the concern that compounds may trap dirt, which allows moisture to form and exacerbate corrosion. Another concern is that the ultraviolet radiation may degrade the coatings.

This experiment focuses on using three commercially available CPCs: CorrosionX, Carwell CP-90, and Fluid Film. Corrosion prevention compounds were selected for this experiment because the previous work done by EXWC showed they were effective. These three compounds were chosen because they are either in the supply system or were recommended by the EXWC corrosion-control officer.

In general, it a good practice to augment outdoor testing with accelerated testing. Although accelerated testing is normally used to identify weaknesses in product design or manufacturing, it can also be used to as a quantitative means for demonstrating the reliability of a product, assuming that product is characterized by a dominant failure mechanism (Thomas 2015). In the case of corrosion preventing compounds, one possible dominant failure mechanism is ultraviolet radiation (UV). The most common type of UV radiation is sunlight, and it is split into UVA, UVB and UVC (U.S. Food and Drug Administration 2020). It is theorized that UV radiation will break down the compounds.

Accelerating the amount of UV radiation the test coupons received should test this theory. Little to no extra corrosion on the accelerated test coupons compared to the field test coupons would suggest the theory is not correct. In addition to providing data on how UV radiation affected the test coupons, accelerated testing was used in this experiment to provide two benefits:

1. It allowed the testers to compare the results of the field test with results under controlled laboratory conditions.
2. It allowed the testers to gather data on long term corrosion in a shorter time than real-world experimentation would allow, given the deadlines for this thesis.

C. RESEARCH QUESTION

The research question to be answered is: "Will one or more of the three selected CPCs provide adequate protection for construction vehicles stored in a desert environment?"

D. LITERATURE REVIEW

Organizations contacted include the DOD Corrosion Office, the Naval Research Laboratory (NRL) and the NAVFAC EXWC corrosion office. Additionally, research was conducted via the internet to determine possible solutions to corrosion. The DOD Corrosion Office confirmed corrosion was a huge issue for the DOD, but the office was not aware of any corrosion studies conducted in a desert environment. Neither NRL nor the NAVFAC EXWC corrosion officer was aware of any corrosion-specific studies done for the desert. The pertinent documents from the literature review are:

NAVFAC P-480 (29JUN16) Management of Expeditionary Equipment. Section 6.3.10 states that NAVFAC S6360-AW-MMO-010 (Corrosion Prevention and Control Technical Manual) is the primary reference for all matters pertaining to corrosion control of expeditionary equipment.

NAVFAC Technical Manual (TM) S6360-AW-MMO-010 (01JAN13) Corrosion Prevention and Control Procedures for U.S. Navy Expeditionary Ground Equipment. Chapter 2 has a very good general discussion of corrosion. Section 2–2 lists the causes and prevention of corrosion. Section 2–4 lists corrosive environments and section 2–6 lists steps to take for corrosion control. The manual lists some guidance for corrosion prevention and control (CPAC) in Section 1–2.

Other research, which contained general information on corrosion, but does not include specific corrosion prevention for the desert, is:

- NAVFAC P-300 (SEP03); TM 4795–34/2 (SEP99) Corrosion Prevention and Control (Rust-proofing and Underbody Coating Procedures for Tactical Vehicles, Trailers, and Engineer Equipment.

- TM-4795-OR/1 (29APR11) Corrosion Prevention and Control Procedures for USMC Ground Combat Equipment.

- MIL-HDBK-808A (USAF) Finish, Protective and Codes for Finishing Schemes for Ground and Ground Support Equipment.

- MIL-HDBK-46164 (02JAN96) Rustproofing for Military Vehicles and Trailers.

- FED-STD-297E (11JAN96) Rustproofing of Commercial (non-tactical) Vehicles.

E. BENEFITS OF EXPERIMENT

This experiment will inform DOD decision makers whether corrosion prevention compounds are a viable method of preventing corrosion in the desert. This experiment allows DOD leadership to make a more informed decision of whether to coat metal objects in the desert with the studied corrosion prevention compounds.

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II. EXPERIMENTAL DESIGN

A. SCOPE OF EXPERIMENT

This experiment consisted of three corrosion prevention compounds applied to unpainted C1010 mild steel in a desert environment during the winter and spring. The scope also included accelerated testing, which involved unpainted steel coated with the same three compounds and subjected to accelerated weathering. Out of scope factors included altering the compound thickness and application methods.

B. TEST COUPONS

The test articles being experimented on are referred to as test coupons in this report. Test coupons were divided into two groups: outdoor test coupons and accelerated test coupons. The outdoor test coupons and the accelerated test coupons were subjected to the same process of clean, weigh, apply the treatment, weigh again, perform the experiment, clean, and weigh again.

The test coupons were ordered from Alabama Specialty Products Inc. and are C1010 mild steel (UNS #G10100) with a bead blasted finish. The test coupons dimensions are 1.000” +/-.020” wide x 2.000” +/-.020” long x .062” +/-.020” thick. See Figure 1.

C. DESCRIPTION OF THE COATINGS

CorrosionX. As of August 1, 2022, the manufacturer’s website describes CorrosionX as an oil-based anti-corrosion spray that utilizes polar bonding and fluid thin film coating (FTFC) technologies to disrupt rust and corrosion on the molecular level (CorrosionX n.d.). The website says CorrosionX contains distillates (petroleum), hydrotreated heavy paraffinic 64742-54-7 and alkenyl amine (the website lists additional details as a trade secret). CorrosionX was selected due to its inclusion in the Naval Facilities Engineering Command (NAVFAC) Technical Manual for Corrosion Prevention and Control Procedures for U.S. Navy Expeditionary Ground Equipment (S6360-AW-MMO-010).

Figure 1. Outdoor test coupons.

Carwell CP-90. The manufacturer's website claims Carwell CP-90 is a blend of rust inhibitors that eliminates moisture containing salt, dirt, and other pollutants from the metal (Carwell n.d.). The manufacturer's website says Carwell CP-90 contains highly refined base oil and various proprietary ingredients. Carwell CP-90 was selected because it meets MIL-STD-3003A (AT).

Fluid Film. The manufacturer's website claims Fluid Film is a unique lanolin-based product that guards against corrosion (Stott 2014). The manufacturer's website says Fluid Film contains refined petroleum oil, hydrotreated light naphthenic 64742-53-6, and hydrotreated heavy paraffinic 64742-54-7. Fluid Film was selected due to a recommendation by the EXWC Corrosion Control Officer (Robert Jamon, discussion with the author, March 2020).

D. EQUIPMENT USED

a. Tooke Gage

The Tooke Gage is a tool for dry-film thickness measurement, and it is equipped with a cutting tip for precision cuts. The Tooke Gage was used to ensure the test coupons received the same size scribe. See Figure 2.

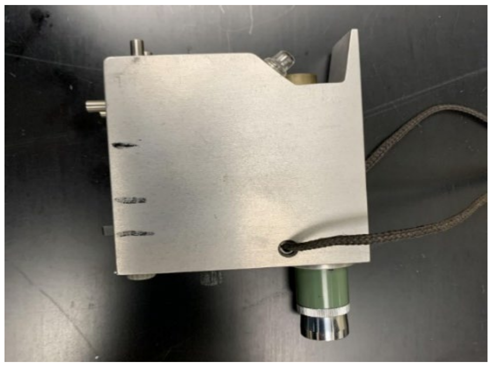


Figure 2. Tooke gage.

b. Fisher Scientific Isotemp Programmable Oven, Model 838F

The Fisher scientific isotemp model 838F oven is a programmable oven with a microprocessor to control operating temperatures ranging from 50 °C to 325 °C. The oven was used to dry the samples to prevent moisture from resulting in the wrong weight measurement. See Figure 3.

Figure 3. Programmable oven.

c. Sartorius Research Semi-micro Balance

The Sartorius Research semi-micro balance has a readability of 0.00001 grams and a maximum weighing capacity of up to 220 grams. The unit has a shield to prevent drafts from interfering with the measurement. The balance was used for exact measurements. See Figure 4.

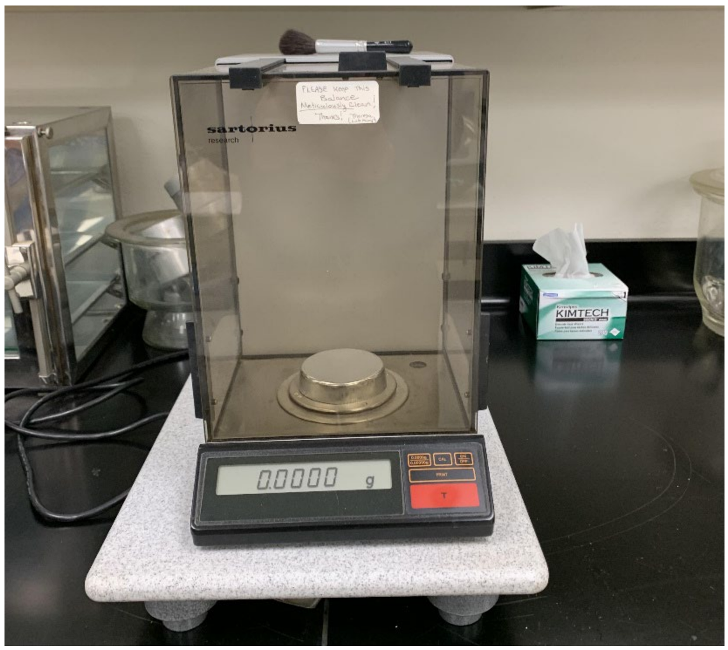


Figure 4. Sartorius Research semi-micro balance.

d. Q-Lab LU-8047-TM QUV/SE Accelerated Weather Tester

The Q-Lab LU-8047-TM QUV/SE accelerated weather tester simulates the damage caused by sunlight (ultraviolet radiation or UV), humidity, and temperature. The manufacturer's website says the tester simulates temperature via special fluorescent UV lamps in the UVA, UVB, and UVC portions of the spectrum; it simulates humidity with a water spray. This tester was used to accelerate weathering of the treatments on the accelerated test coupons. See Figure 5.

Figure 5. Accelerated weather tester.

e. Branson 2200 Ultrasonic Cleaner

The Branson 2200 ultrasonic cleaner uses a 40 kilohertz frequency for rapid cleaning. The unit has a compact, stainless-steel tank that provides high quality cleaning. The ultrasonic cleaner was used to clean the test coupons to ensure all corrosion was removed. See Figure 6.

Figure 6. Branson 2200 ultrasonic cleaner.

E. EXPERIMENTAL PROCEDURE FOR THE OUTDOOR TEST COUPONS

The outdoor test coupons were prepared by cleaning with a degreasing agent (dishwashing soap) to remove contaminants, rinsed with di-ionized water, dried in an oven for 15 minutes at 120 °C, scribed (intentionally scratched to make corrosion easier to form) with a Tooke Gage tool, and weighed to determine an initial value. Test coupon A0643 was cut so the metal could be placed under an electron microscope and examined in detail at the microscopic level. Three of the test coupons were left untreated to serve as the control group, six were coated with Carwell CP90, six were coated with Fluid Film, and six were coated with CorrosionX. See Figure 7.

The test coupons were attached to a wooden pallet via zip ties and placed at a thirty-degree angle relative to the sun at the western area research test and evaluation center (WARTEC) in the Marine Corps Air Ground Combat Center in Twentynine Palms, California, on 1 November 2021. See Figure 8.

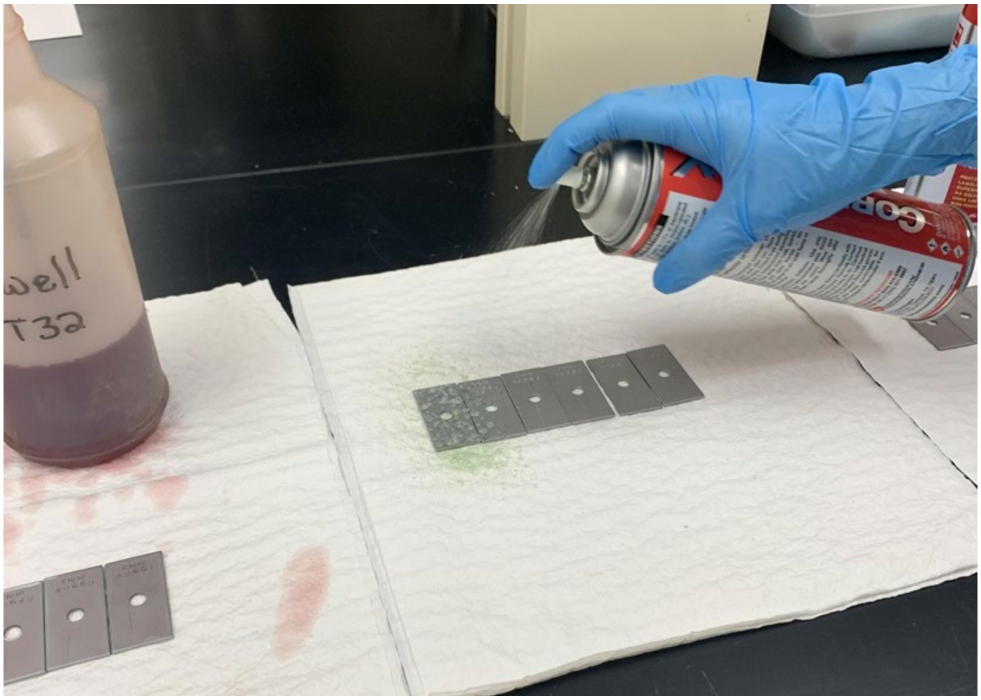


Figure 7. Coating test coupons with CorrosionX.

Figure 8. Outdoor test coupons at the site.

This site was selected because it has a locked, fenced-in area to secure the outdoor test coupons. The area is flat desert, exposed to the wind except for a single-story building about fifteen yards to the south. The building's shadow never covered the test coupons. The test coupons were recovered on 19 May 2022.

F. STEPS TAKEN AFTER RECOVERY FROM THE DESERT

After the test coupons were recovered from the desert, the test coupons were weighed and placed in the ultrasound cleaner with a solution of ammonium citrate and water. The ultrasound cleaner ran for 30 minutes, then the test coupons were cleaned with dishwashing soap and dried in the oven for 15 minutes at 120 °C. After the test coupons cooled, they were weighed again. See Figure 9 for a picture of the recovered outdoor test coupons and Figure 10 for a picture of an individual test coupon.

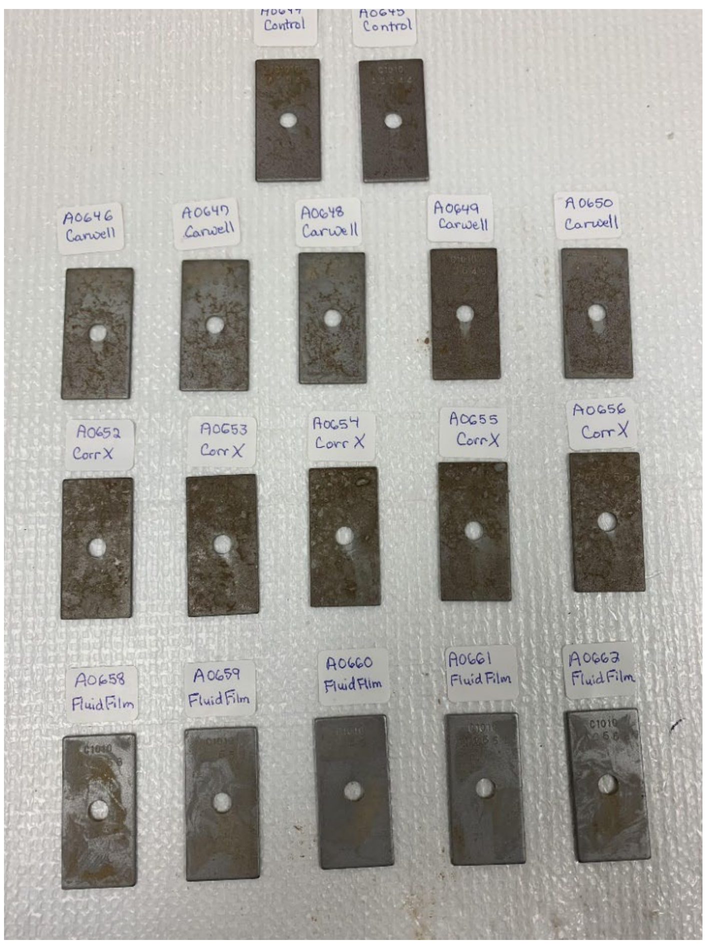


Figure 9. Outdoor test coupons after exposure.

Figure 10. Individual outdoor test coupon after exposure.

After six months, the outdoor test coupons were collected, cleaned with an ultrasonic cleaner, and weighed again. See Appendix A for the test coupon number, weight of the test coupon and the treatment each test coupon received. The difference between the initial and final weights were used to determine how much metal was lost to corrosion.

G. ACCELERATED TEST COUPONS

On 23 April 2022, thirty test coupons were placed inside a Q-Lab LU-8047-TM QUV/SE accelerated weather tester set at 113 degrees Fahrenheit. The test coupons were exposed to an irradiance of 0.83 W/m2 at a wavelength of 340 nm in 168-hour cycles (approximately one week of test time). The humidity level was set to the level experienced in Monterey, California. See Appendix B for the table containing the initial starting weight and treatment for the accelerated test coupons.

H. METALLOGRAPHY

The accelerated test coupons were cut using a high-speed saw and mounted in Struers DuroFast resin. The resin is a thermoplastic resin used for hot mounting of samples with good edge retention. The resin was formed and set, with the sample using a Struers

Citopress hot mounter. Once mounted, samples were polished using a Struers grinding wheel on 320-, 600-, and 1200-grit silicon carbide grinding paper. The grinding wheel was set to 200 RPMs and samples were polished with the grinding papers for 5 – 45 minutes. After the 1200-grit paper, polishing proceeded on polishing cloth dosed with 1 μm diamond in water suspension at 100 RPMs for 60 minutes. Samples were imaged for quality of polishing after each step using a Nikon Epiphot 200 optical microscope. Higher resolution imaging of the microstructure of samples were obtained in a Zeiss Neon 40 dual-beam scanning electron microscope (SEM) as seen in Figure 11. The settings used in the SEM were 15 – 20 kV, 20 μm aperture, and ~ 5.0 mm working distance. SEM images were taken with both the in-column and chamber electron detectors.

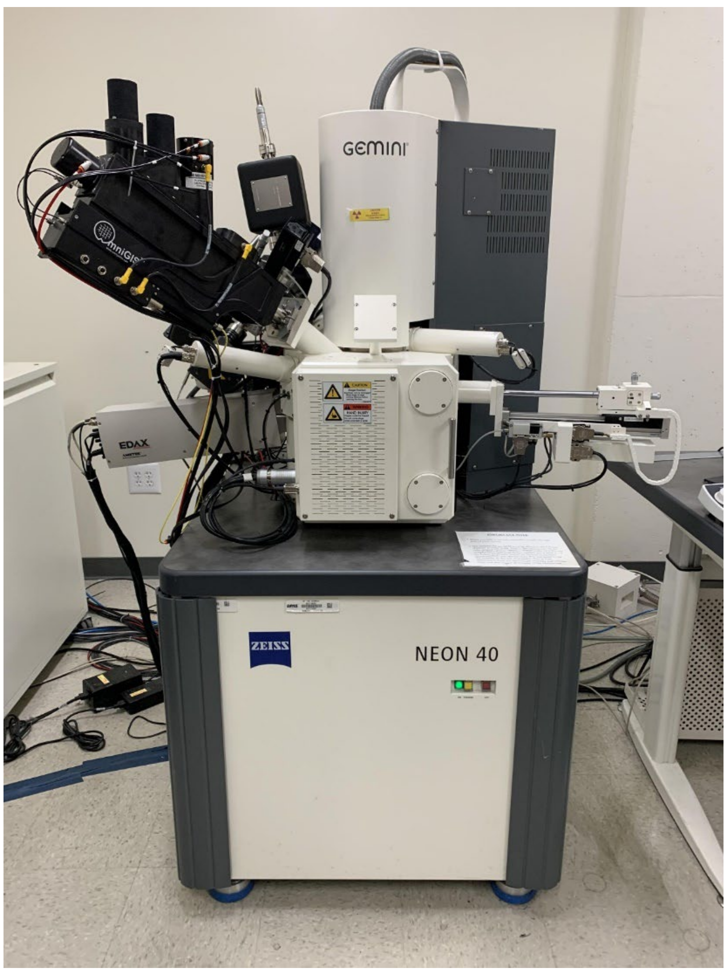


Figure 11. Zeiss Neon 40 scanning electron microscope.

I. HISTORICAL ENVIRONMENTAL CONDITIONS AT THE OUTDOOR EXPERIMENTAL SITE

From November 2021 to May 2022 the outdoor test coupons were exposed to the desert climate. The climate is a desert environment characterized by three months of extreme heat in the summer, a short rainy season in the winter and very little humidity.

J. DATA ANALYSIS METHOD

The data was analyzed by analysis of variance (ANOVA). ANOVA analyzes the variation among the groups and compares it to the variation between the groups to determine if there is a difference in the means. Calculations were performed by Minitab, a statistical software package. ANOVA determines if there is a difference between the means of two or more groups, not which group performed better than the other groups. To determine which of the means performed better, a post-hoc test like the Tukey HSD test was used. Again, Minitab was used to calculate the value of the Tukey HSD test. The original data analysis plan was to use ANOVA followed by Tukey, but inconsistencies in the results forced other tests to be used. The additional tests were the individual t-tests and Fisher's Pairwise comparison. See Table 1 for the groups being compared.

Table 1. Groups being compared.

CPC	Compared to
Control	Carwell
CorrosionX	Carwell
Fluidfilm	Carwell
CorrosionX	Control
Fluidfilm	Control
Fluidfilm	CorrosionX

ANOVA was the statistical test used to compare the mean weight loss of the test coupons for this experiment. The outdoor test coupons and the accelerated test coupons were not combined for the analysis—each test condition was examined separately. For both the outdoor and accelerated testing the groups being compared consisted of control, CorrosionX, Fluidfilm, and Carwell. The loss in weight represents the effects of corrosion and the environment during the experimental period. In ANOVA, the tester selects a null hypothesis, which is always the means are equal, and an alternative hypothesis, which is the means are different. A level of significance (denoted by the Greek letter α) is then chosen (normally .01, .05 or .1) and if the probability of getting a random sample is below that level of significance, it is assumed the null hypothesis should be rejected. For this experiment, the null hypothesis is:

H_o = the means of the four groups are equal

H_1 = at least one of the means is different

The level of significance, α, is set at .05. This indicates that there is only a 5% chance the results were due to random variability and not the treatments.

III. RESULTS

A. PRELIMINARY EXAMINATION OF THE TEST COUPONS

On 2 February 2022, four of the outdoor test coupons were recovered for preliminary analysis. The test coupons were selected at random and represented one from each group, including the control. A visual inspection showed that rust was forming on the untreated test coupons, but not the treated test coupons. Pictures of the preliminary analysis are unusable due to incorrect camera settings.

B. WEATHER DURING THE EXPERIMENT

Comparing the temperature and precipitation data taken at the Twenty-nine Palms airfield, California, to the historical average, the experiment was conducted in hotter and drier conditions than the historical average would suggest. The temperature was over thirteen degrees hotter, and the precipitation was less than 1/3 of an inch, instead of the almost three inches of the historical average (Weatherunderground n.d.). See Table 2 for the exact difference between expected and observed temperature and precipitation. See Table 3 for a listing of the temperature and precipitation by month.

Table 2. Observed vs. historical temperature and precipitation.

	Temperature (°F) daytime average	Precipitation (in.)
Observed	67.09	0.32
Historical average	53.65	2.9

Average daily temperature by month.

	Temperature	Precipitation
November	72.5	0
December	58.51	0.2 cm
Jan 2022	61.31	0.0
Feb 2022	64.01	.1
Mar 2022	69.24	0
April 2022	76.94	0.02

C. OUTDOOR TEST COUPONS RESULTS

The mean starting weight of the test coupons was 15.29000 grams, the mean finishing weight was 15.27859 grams, and the mean percentage of weight loss was 0.00097 grams. The final recorded weights of the outdoor test coupons are listed in appendix C.

D. ACCELERATED TEST RESULTS

The mean starting weight of the test coupons was 16.10586 grams, the mean finishing weight was 16.11158 grams, and the percentage of weight change was 1.000356—the test coupons gained weight after the accelerated testing. This result was unexpected and possible explanations include a mis-calibrated scale or a data recording mishap. Another possible explanation is the accelerated weathering removed the coatings, which allowed the accelerated test coupons to rust and that rust held in water, which increased the weight of the test coupon.

The results of the ANOVA test show a p value of 0.03, below the .05 level of significance, indicating that at least one of the means is significantly different than the rest. The post hoc Tukey HSD shows that there is a significant difference between Fluid Film and CorrosionX and that difference is statistically significant at the 0.05 level of significance. See Figure 12. See Appendix D for the table containing the final weights and Appendix E for the complete Minitab analysis.

E. MICROSTRUCTURE

No differences in microstructure were observed between the control sample and the treated samples. Additionally, there was no indication of interaction between the coatings and the steel microstructure of the samples. Figure 13 shows the microstructure of sample A0920, one of the samples that was coated with Carwell CP-90. The low magnification image in Figure 13a) reveals the complete thickness of the sample after etching. The microstructure is uniform as there are no apparent deformations except for scratches left over from the grinding and polishing process. In Figure 13b), the higher magnification image shows the two-phase structure typical of low alloy carbon steels. Red arrows indicate grains of pearlite, a lamellar phase composed of alternating bands of ferrite and iron carbide. The rest of the grains with zero contrast differences within, are ferrite grains. The low number of pearlite grains again indicates this steel is a low alloy steel. These steels are commonly found throughout the military and industry for their low cost but are quite susceptible to corrosion as compared to stainless steels. Figure 13c) and d) are low and high magnification SEM images revealing slight over-etching of the cross-section.

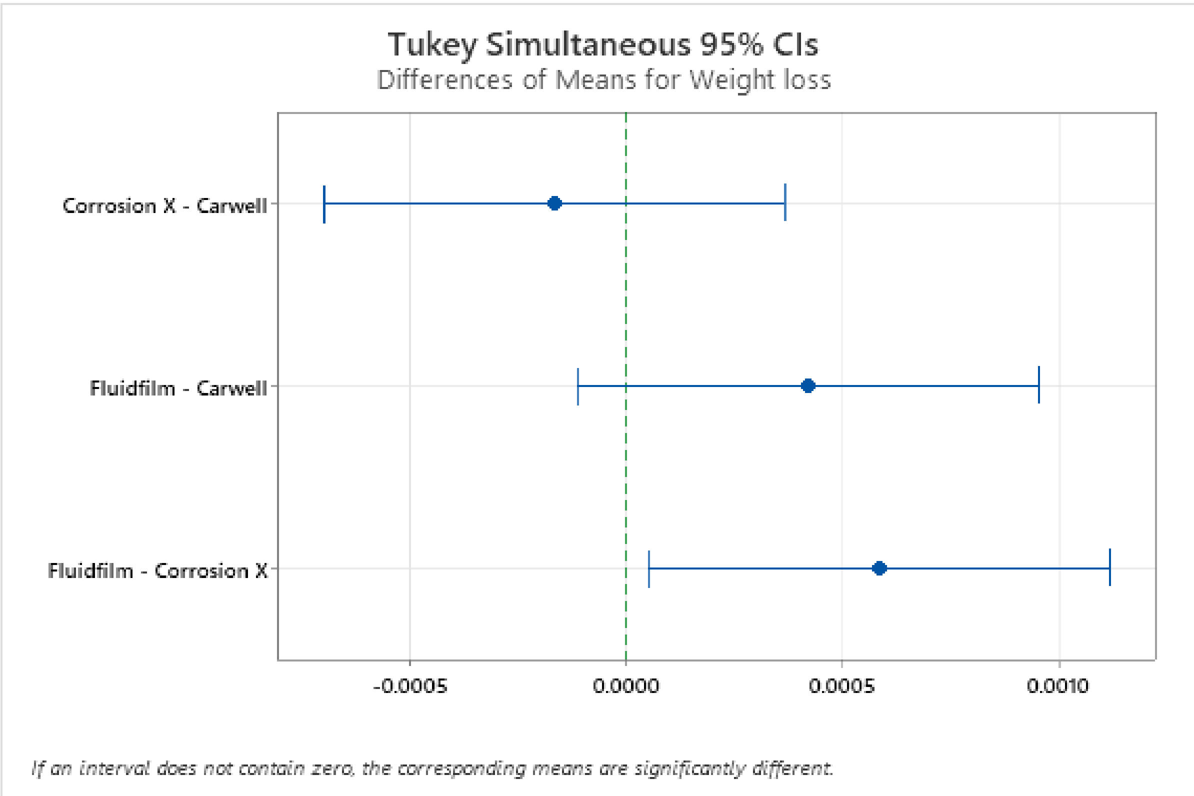
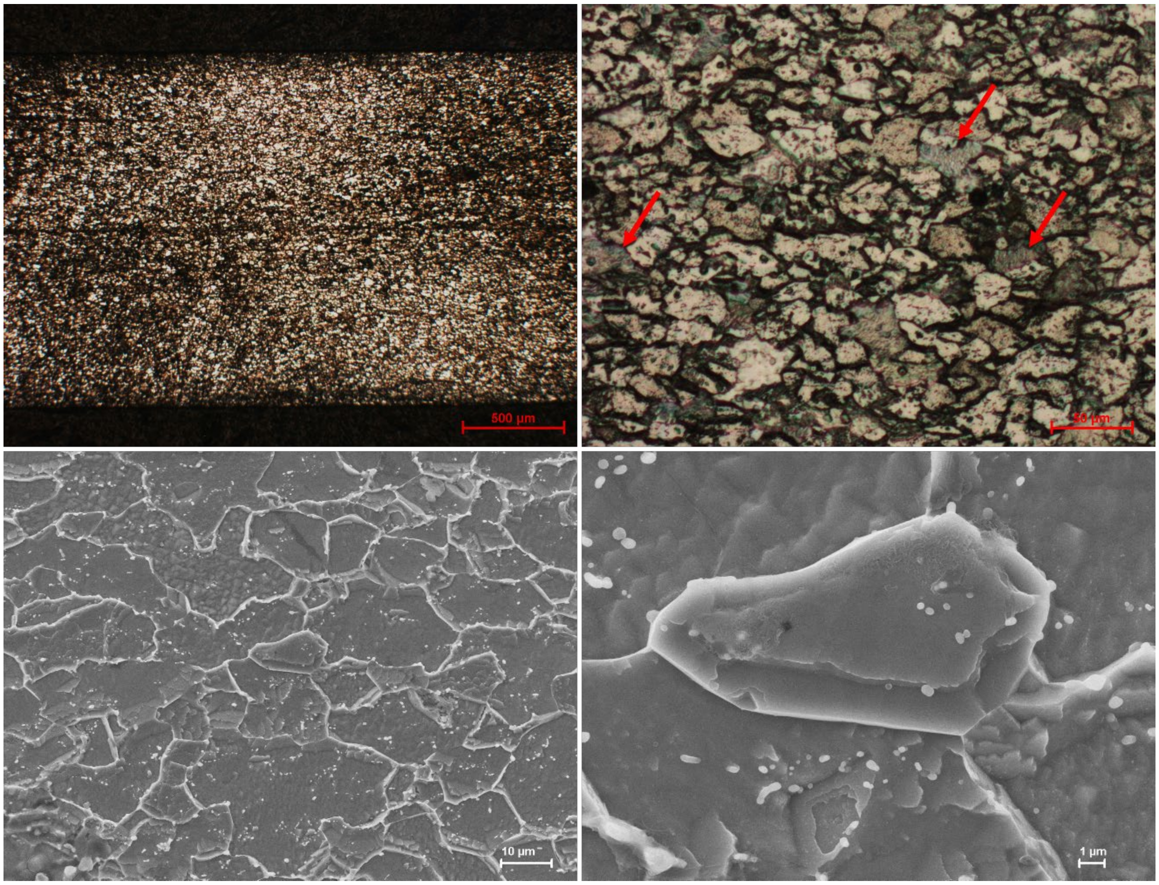


Figure 12. Tukey HSD test results.



Low magnification optical image (a). High magnification optical image (b); red arrows indicate grains of pearlite. Low magnification SEM image (c). High magnification SEM image (d). Note the differences in scale (a)–(d).

Figure 13. Microstructural optical images of sample A0920.

F. STATISTICAL ANALYSIS ON THE OUTDOOR TEST COUPONS

The one-way ANOVA test was run using Minitab and the result was a p value of 0.032, indicating a significant difference in at least one of the means. The small p value triggered the next test, Tukey HSD to determine which of the means was statistically different than the rest. Unfortunately, the Tukey test determined that none of the means were statistically different. See Appendix F for the complete Minitab results on the Tukey HSD post-hoc test.

This presented a conundrum: the small p value in the ANOVA test indicates there is a difference in means and the null hypothesis should be rejected; however, the subsequent Tukey HSD test indicated that none of the means were significantly different, meaning the null hypothesis should be accepted. This is a very unusual, but not unheard of, result. There are at least two possible explanations why the two tests, which are usually aligned, might give different results. The first is the sample size is not large enough for the Tukey HSD test; another possible explanation is the post hoc test corrects for multiple comparisons, which makes the test more conservative, thus the post hoc test fails to detect a difference when the means are borderline different (MacDougall, 2020).

A closer examination of the data suggests the second explanation has some validity; as Figure 14 illustrates, the difference between Fluid Film and the control group is right on the border of being statistically different. To read the graph, if an interval does not contain zero, the corresponding means are different and the result is statistically significant at the chosen level of significance (in this case, 0.05).

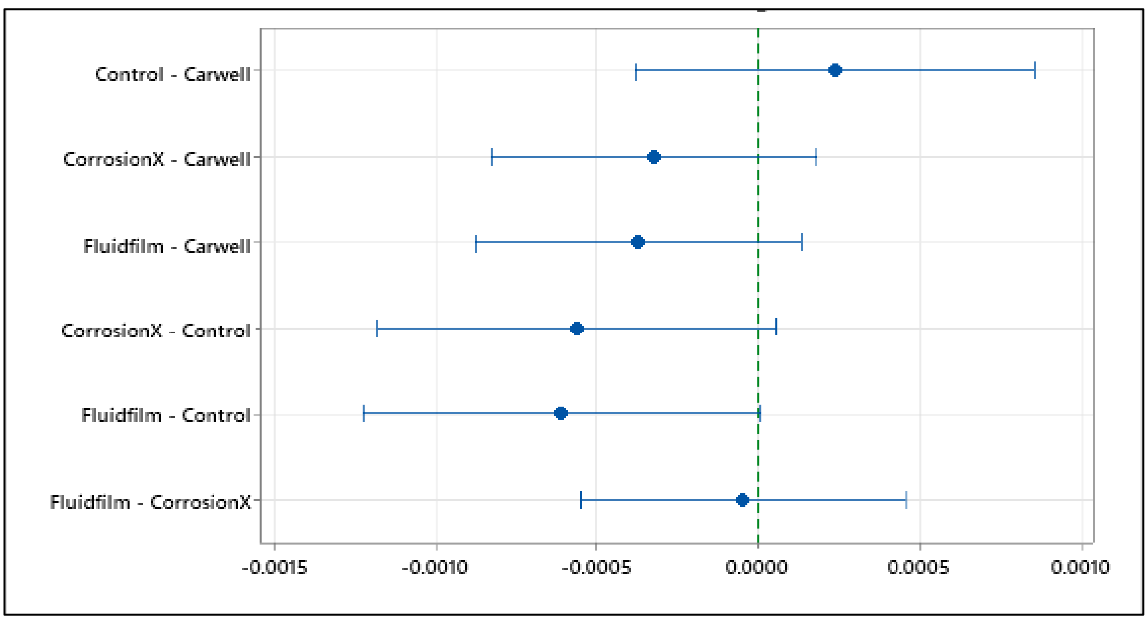


Figure 14. Tukey HSD 95% confidence intervals.

To ensure the analysis was done correctly, additional analysis was done on the data. ANOVA relies on several underlying assumptions, such as a normal distribution and unequal error variances; those assumptions are checked with the normal probability plot, and a "versus fits" graph.

The normal probability plot is a good indicator if the data is normally distributed. The data is plotted against a hypothetical straight line and a straight line, or a close approximation of a straight line, indicates normality. The normal probability plot for this data indicates the data is normally distributed. See Figure 15 for the normal probability plot associated with this data set.

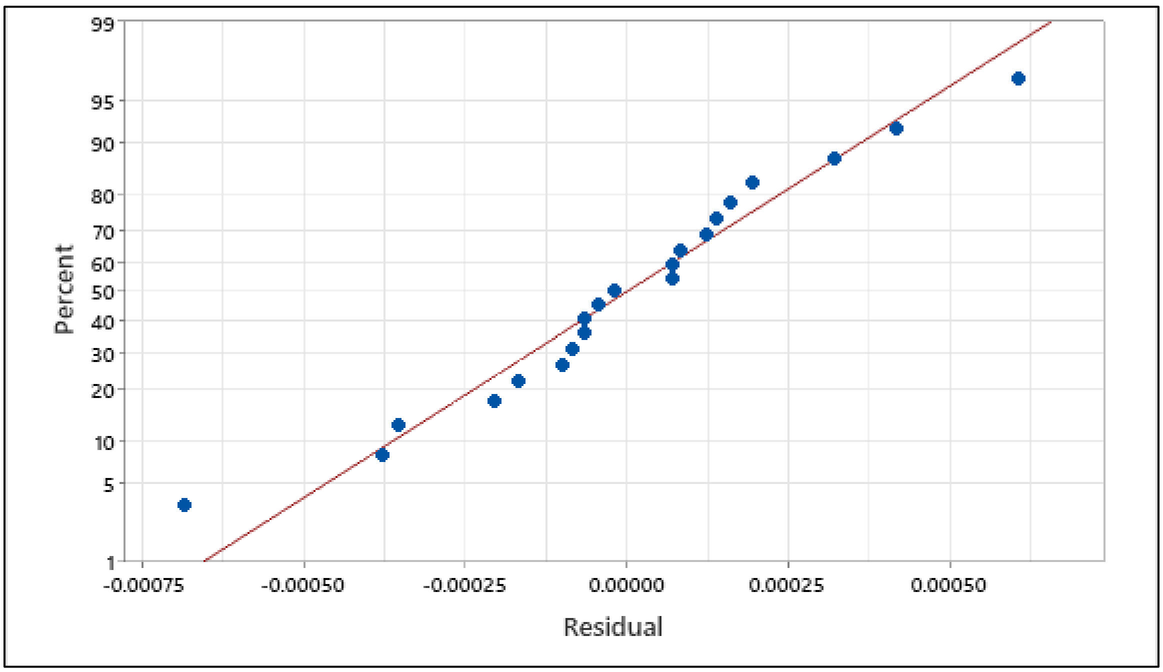


Figure 15. Normal probability plot.

A versus fits graph plots residuals on the Y axis, fitted values on the X axis and ideally has values scattered randomly around the zero line (Penn State n.d.). The versus fit graph for this particular data set strongly suggests linearity. This is a strong indication that ANOVA is not an appropriate method of analysis for this data set. See Figure 16.

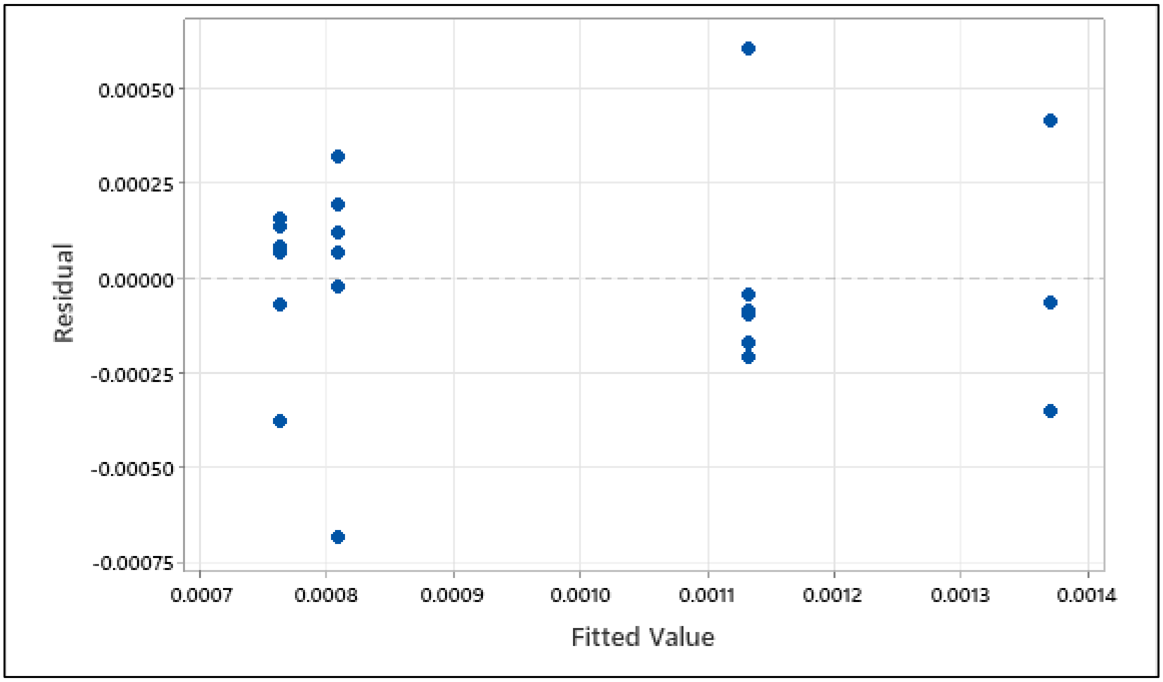


Figure 16. Versus fit graph.

At this point there are two findings that suggest the planned ANOVA test is not a valid method to analyze this data set:

1. The ANOVA and the Tukey test do not match
2. The versus fit suggests the data exhibits unequal error variances

Due to the above issues, a different post-hoc test was needed. Two potential tests are Fisher's Pairwise Comparison test and individual t-tests. Both statistical tests were done and the results compared.

The next statistical analysis conducted was Fisher's Pairwise Comparison test. This post hoc test determined that there is a difference in the means, and this difference is statistically significant at the .05 level. Figure 17 illustrates both Fluid Film and CorrosionX performed better than the control group. To read the graph, intervals that do not contain zero have means that are different and the difference is statistically significant at the chosen level of significance (0.05 for these calculations). See Appendix G for the complete Minitab analysis on the Fisher pairwise comparisons.

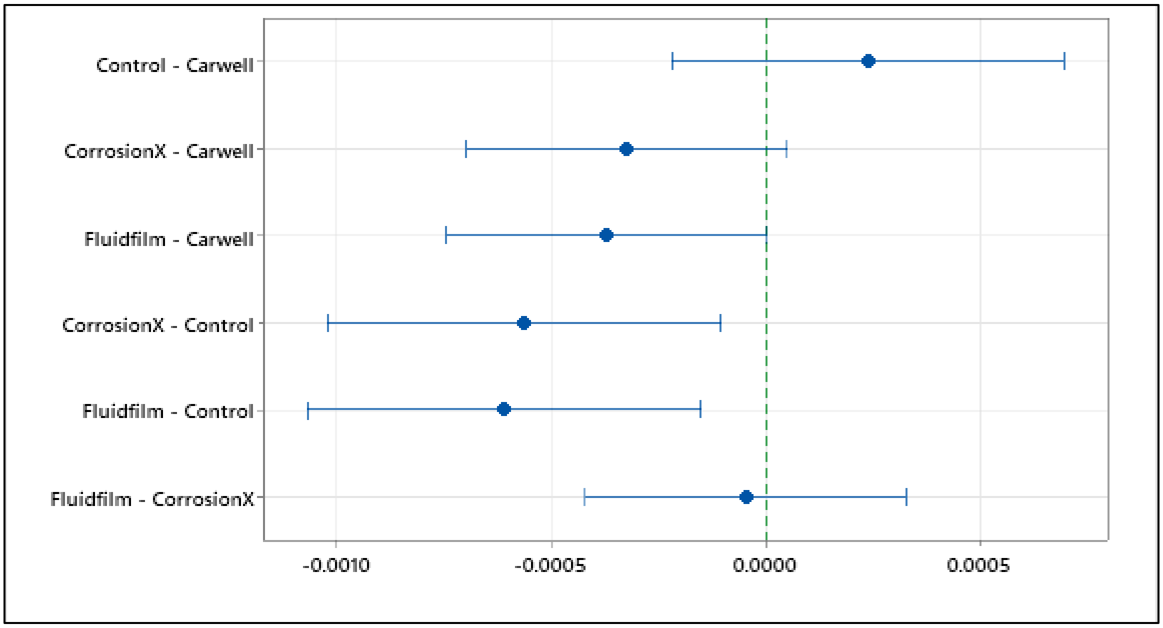


Figure 17. Fisher individual 95% confidence interval.

The next step was to run t-tests, with the six possible combinations compared to each other. None of the results were significant at the .05 level. See Table 4 for the comparisons and Appendix H for the complete Minitab results on the t-tests. Individual

Table 3. Individual t-tests.

CPC	Compared to	P value
Carwell CP-90	control	0.421
CorrosionX	control	0.127
Fluid Film	control	0.127
Carwell CP-90	CorrosionX	0.125
Carwell CP-90	Fluid Film	0.38
CorrosionX	Fluid Film	0.788

IV. CONCLUSION AND FUTURE WORK

A. CONCLUSIONS

This experiment consisted of an accelerated and an outdoor portion. The data from the accelerated experiment were analyzed with ANOVA and Tukey's HSD and concluded CorrosionX was the preferred coating.

Data from the outdoor experiment was analyzed with ANOVA, Tukey HSD, Fisher's pairwise comparisons and individual t-tests. The ANOVA analysis concluded there was a difference in the means and Fischer's analysis concluded that difference was caused by superior performance by CorrosionX and Fluid Film. The Tukey HSD and individual t-tests concluded there is no difference in the means.

It is assumed the outdoor experiment better represents the real world because it is difficult, if not impossible, for accelerated tests to replicate the natural environment with 100% accuracy. Thus, although both the outdoor and accelerated experiments are valid, the results of the outdoor experiment are weighted more heavily than the accelerated results and Fluid Film is considered on par with CorrosionX.

The point of the experiment was to determine if corrosion-prevention coatings would slow the rate of corrosion in a desert environment and there is some evidence in the outdoor experiment to indicate the answer to that question is yes. The results of the Fisher's pairwise comparison's test indicate bare steel coated with either Fluid Film or CorrosionX will corrode slower than untreated metal. The third coating, Carwell CP-90, did perform better than the control group, but the difference is not statistically significant at the 0.05 level (i.e., it could have been random chance that produced the different result). There is nothing in the results that indicates either Fluid Film or CorrosionX is superior to the other so if the Navy wants to go this route, they should use the cheapest option.

However, there some caveats regarding the results. Any experiment can produce an unlikely, difficult to reproduce, result. For example, the probability of flipping a perfectly balanced coin six times and receiving six heads is 0.0156, not zero, so unusual results will happen in real life. The very fact that α is set to 0.05 means that 5% of the time the tester should expect an unusual result. This experiment may represent that 5% as the following anomalies are present:

1. The ANOVA analysis indicated the means are different
2. The subsequent Tukey analysis indicated there are no significant differences in the means
3. Fisher's pairwise comparisons indicated CorrosionX and Fluid Film are significantly different than the control group
4. The subsequent t-tests indicated there is no significant differences in the means of CorrosionX, Fluid Film, Carwell CP-90 and the control group

There are three factors that are probably contributing to these findings:

1. The sample size was too small. A small sample size can produce statistically significant results if the effect is large enough, but this experiment produced relatively small effects which makes it difficult to separate the signal from the noise.
2. The environmental conditions were not ideal for a corrosion experiment. The area received approximately 11% of the expected precipitation and that probably slowed the rate of corrosion. It is very possible that conducting the same experiment during a year with a normal amount of precipitation would have produced very different results.
3. The time period was too short, especially given the lack of precipitation. Rust did form on the test coupons, but not sufficiently for all of the statistical analysis to conclusively agree on one recommended approach. A longer test period presumably would have allowed more rust to form, which would reduce the noise in the experiment.

Although the ANOVA and Fisher's analysis conducted on the outdoor experimental data indicates either CorrosionX or Fluid Film is an effective way to fight corrosion in the desert, the author believes there are enough remaining questions posed by this data set to suggest this was an unusual result and the experiment should be repeated.

In summary, this experiment consisted of a six-month study outdoor study with bare metal test coupons treated with corrosion prevention compounds and exposed to a dry climate for a six-month period; as well as 30 additional samples subjected to accelerated aging. Some of the analysis suggest that placing unused construction equipment in the desert and treating the metal with a corrosion prevention compound will improve corrosion resistance and save the NECC-PAC manpower and money. However, the sample size was small, the testing timeframe was short, and the environment did not reflect a normal year, so the results are questionable. This experiment should represent a starting point for understanding how CPCs can protect metal in a desert environment, not a finishing point.

B. FUTURE WORK

Future research could focus on the following:

- Conduct another experiment with a larger sample size tested over a longer timeframe. A fair question to ask of any experiment is "were the environmental conditions during the experiment different enough from expected conditions that the experiment's conclusions are not valid?" For this experiment, the sample size was small, the duration short, and the weather patterns were unusual enough during the experiment to justify a second experiment.

- Conduct another experiment to test different types of metal, such as stainless or maraging steel, other high yield steels, and copper alloys like brass or bronze. The scope of this experiment was limited to low-alloy carbon steel, but the U.S. Navy is also concerned with how the desert environment affects other metals

- Conduct an experiment to determine how will the CPCs affect the U.S. Navy's standard chemical attack resistant coatings (CARC). The Navy coats vehicles with CARC, a coating designed to repeal chemical agents, but CARC coatings are not designed to stop corrosion. It is not known if CPCs would interfere with the chemical-attack preventive nature of CARCs, or if the CARC would interfere with the corrosion prevention of the CPCs.

- Conduct an experiment with other corrosion prevention compounds than the three this study analyzed. There are more CPCs than those listed in this report; some of the CPCs that could be researched include: Jotacote Universal S120, polysulfide-based compounds such as Masterbond, and ArmorThane.
- Conduct an experiment to determine how the harsh desert environment will impact other materials. Although metal constitutes most of a vehicle, other materials, such as rubber or bullet-proof glass are also present. It is possible the benefits of metal-preservation could be negated by the extra damage done to tires and bullet proof glass. Bullet-proof glass is expensive, and the vehicles stored in the desert had extensive damage to the glass (Neal Pinchevsky, discussion with the author, May 2019). However, it is possible the bullet-proof glass deteriorated due to manufacturing defects, not due to the desert environment (Arias et al. 2020).
- Conduct an experiment to compare test coupons placed in the desert with test coupons placed in a coastal area. The first EXWC experiment placed coupons in a coastal area and this experiment placed test coupons in the desert, but a side-by-side comparison will enable researchers to directly compare the two environments.
- Conduct an experiment to test different coating thickness. There is almost certainly an optimum coating thickness, but the ideal amount of coating to add is not known at this time.
- Conduct an experiment with accelerated aging that exceeds a six-week period.

C. RECOMMENDATIONS

Conduct the experiment again, with a larger sample size and a prolonged time. The author recommends 45 test coupons per group (180 total) for a two-year period. Five of the samples should be removed at six-, 12-, and 18-month intervals for examination under an electron microscope. This will allow the experimenter to understand how the metal is corroding over time, while still allowing 30 samples per group for statistical analysis. Other recommendations include:

- Conduct the experiment again, coating metals besides steel.
- Conduct an experiment to determine the interaction between CPCs and CARC.
- Conduct an experiment with different CPCs.
- Conduct an experiment to determine how to prevent non-metal materials, such as rubber or glass, from deteriorating in the desert.
- Conduct an experiment with a set of test coupons in the desert with a similarly treated set of test coupons on the coast.
- Conduct an experiment with varying amounts of CPCs applied to the metal.

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APPENDIX A. TABLE OF INITIAL WEIGHTS

Table 4. Initial weights.

Test coupon number	Weight of coupon (in grams)	Weight of coupon after scribe (in grams)	Treatment
A0643	15.4072	15.4075	Control
A0644	15.4384	15.4384	Control
A0645	15.4773	15.4777	Control
A0646	15.4859	15.4859	Carwell
A0647	15.4983	15.4976	Carwell
A0648	15.4635	15.4623	Carwell
A0649	15.4733	15.4735	Carwell
A0650	15.4705	15.4712	Carwell
A0651	15.4877	15.4880	Carwell
A0652	15.4320	15.4312	CorrosionX
A0653	15.4666	15.4664	CorrosionX
A0654	15.3754	15.3757	CorrosionX
A0655	15.4727	15.4724	CorrosionX
A0656	15.4942	15.4938	CorrosionX
A0657	15.4035	15.4038	CorrosionX
A0658	15.5178	15.5180	Fluid Film
A0659	15.5304	15.5301	Fluid Film
A0660	15.5068	15.5054	Fluid Film
A0661	15.4015	15.4005	Fluid Film
A0662	15.4528	15.4518	Fluid Film
A0663	15.3969	15.3972	Fluid Film

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APPENDIX B. DATA FOR THE ACCELERATED TEST COUPONS

Table 5. Accelerated test coupon data.

	As-received	Treated	First Week
Sample	Mass (g)	Mass (g)	Mass (g)
A0920	16.1508	16.7293	
A0921	16.1524	16.619	
A0922	16.1107	16.6622	
A0923	16.112	16.5361	
A0924	16.0963	16.2812	
A0925	16.1064	16.526	
A0926	16.0647	16.4119	
A0927	16.1313	16.5341	
A0928	16.1065	16.3828	
A0929	16.1155	16.4876	
A0930	16.074	16.092	
A0931	16.1097	16.1456	
A0932	16.1057	16.1368	
A0933	16.115	16.1401	
A0934	16.1431	16.17	
A0935	16.0988	16.1345	
A0936	16.1182	16.1506	
A0937	16.1069	16.156	
A0938	16.13	16.1625	
A0939	16.1047	16.1488	
A0940	16.0834	16.182	
A0941	16.0693	16.185	
A0942	16.067	16.1785	
A0943	16.083	16.1842	
A0944	16.096	16.1949	
A0945	16.1002	16.2047	
A0946	16.1253	16.2702	
A0947	16.0969	16.1904	

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APPENDIX C. TABLE OF FINAL WEIGHTS

Table 6. Final weights.

Test coupon number	Weight of coupon (in grams)	Weight of coupon after scribe (in grams)	End of test - dirty	End of test - cleaned	percentage of weight loss	Treatment
A0643	15.4072	11.9175		11.8962	0.001787288	Control
A0644	15.4384	15.4384	15.441	15.4227	0.001016945	Control
A0645	15.4773	15.4777	15.4811	15.4575	0.001305103	Control
A0646	15.4859	15.4859	15.4882	15.471	0.000962166	Carwell
A0647	15.4983	15.4976	15.5006	15.4816	0.001032418	Carwell
A0648	15.4635	15.4623	15.4655	15.448	0.00092483	Carwell
A0649	15.4733	15.4735	15.4767	15.4567	0.001085727	Carwell
A0650	15.4705	15.4712	15.4719	15.455	0.001047107	Carwell
A0651	15.4877	15.488		15.4611	0.001736829	Carwell
A0652	15.432	15.4312	15.4367	15.4157	0.001004458	CorrosionX
A0653	15.4666	15.4664	15.4712	15.452	0.000931051	CorrosionX
A0654	15.3754	15.3757	15.3838	15.3622	0.000878009	CorrosionX
A0655	15.4727	15.4724	15.4779	15.4602	0.000788501	CorrosionX
A0656	15.4942	15.4938	15.4993	15.4763	0.001129484	CorrosionX
A0657	15.4035	15.4038		15.4019	0.000123346	CorrosionX
A0658	15.5178	15.518	15.5344	15.5037	0.000921511	Fluidfilm
A0659	15.5304	15.5301	15.5516	15.517	0.000843523	Fluidfilm
A0660	15.5068	15.5054	15.525	15.4925	0.000831968	Fluidfilm
A0661	15.4015	15.4005	15.4104	15.3898	0.000694783	Fluidfilm
A0662	15.4528	15.4518	15.4631	15.4379	0.000899572	Fluidfilm
A0663	15.3969	15.3972		15.3913	0.000383187	Fluidfilm

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APPENDIX D. TABLE OF ACCELERATED TESTING

Table 7. Accelerated testing data.

	As-received	Treated	First Week	Second Week	Third Week	Fourth Week	Fifth Week	Sixth Week
Sample	Mass (g)	Mass (g)	Mass (g)	Mass (g)	Mass (g)	Mass (g)	Mass (g)	Mass (g)
carwell								
A0920	16.1508	16.7293	16.3005	16.2032	16.1766	16.1636	16.1575	16.1470
A0921	16.1524	16.6190	16.2676	16.1981	16.1660	16.1587	16.1535	16.1480
A0922	16.1107	16.6622	16.2070	16.1613	16.1265	16.1183	16.1124	16.1074
A0923	16.1120	16.5361	16.1907	16.1451	16.1232	16.1165	16.1124	16.1087
A0924	16.0963	16.2812	16.1646	16.1322	16.1105	16.1073	16.1026	16.0970
A0925	16.1064	16.5260	16.2100	16.1490	16.1310	16.1270	16.1239	16.1201
A0926	16.0647	16.4119	16.1851	16.1423	16.1180	16.1114	16.1057	16.1012
A0927	16.1313	16.5341	16.2100	16.1718	16.1445	16.1394	16.1341	16.1315
A0928	16.1065	16.3828	16.1850	16.1475	16.1261	16.1208	16.1200	16.1165
A0929	16.1155	16.4876	16.1806	16.1461	16.1234	16.1178	16.1138	16.1126
corrosion x								
A0930	16.0740	16.0920	16.0813	16.0778	16.0764	16.0760	16.0745	16.0781
A0931	16.1097	16.1456	16.1200	16.1134	16.1123	16.1114	16.1108	16.1104
A0932	16.1057	16.1368	16.1126	16.1063	16.1087	16.1072	16.1063	16.1081
A0933	16.1150	16.1401	16.1186	16.1170	16.1161	16.1160	16.1176	16.1143
A0934	16.1431	16.1700	16.1476	16.1449	16.1441	16.1432	16.1430	16.1425

A0935	16.0988	16.1345	16.1080	16.1035	16.1020	16.1011	16.1030	16.0990
A0936	16.1182	16.1506	16.1237	16.1200	16.1209	16.1208	16.1226	16.1208
A0937	16.1069	16.1560	16.1211	16.1124	16.1124	16.1107	16.1114	16.1102
A0938	16.1300	16.1625	16.1380	16.1333	16.1349	16.1342	16.1384	16.1340
A0939	16.1047	16.1488	16.1126	16.1071	16.1087	16.1072	16.1107	16.1057
Fluid Film								
A0940	16.0834	16.1820	16.1085	16.0966	16.0931	16.0919	16.0957	16.0940
A0941	16.0693	16.1850	16.1164	16.0921	16.0885	16.0846	16.0861	16.0811
A0942	16.0670	16.1785	16.0954	16.0815	16.0782	16.0745	16.0780	16.0723
A0943	16.0830	16.1842	16.1125	16.0987	16.0942	16.0924	16.0967	16.0947
A0944	16.0960	16.1949	16.1251	16.1143	16.1126	16.1079	16.1090	16.1077
A0945	16.1002	16.2047	16.1374	16.1153	16.1135	16.1102	16.1133	16.1123
A0946	16.1253	16.2702	16.1745	16.1526	16.1459	16.1426	16.1447	16.1423
A0947	16.0969	16.1904	16.1242	16.1164	16.1113	16.1085	16.1096	16.1084
A0948	16.1143	16.1711	16.1411	16.1290	16.1266	16.1241	16.1256	16.1240
A0949	16.0877	16.1775	16.1206	16.1105	16.1034	16.0991	16.1000	16.0976

APPENDIX E. ACCELERATED TESTING MINITAB RESULTS

WORKSHEET 1

One-way ANOVA: Weight loss versus Treatment

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05
Rows unused	1

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Treatment	3	Carwell, Corrosion X, Fluid Film

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	0.000002	0.000001	3.98	0.030
Error	27	0.000006	0.000000		
Total	29	0.000008			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0004788	22.79%	17.07%	4.67%

Means

Treatment	N	Mean	StDev	95% CI
Carwell	10	1.00027	0.00080	(0.99996, 1.00058)
Corrosion X	10	1.00011	0.00011	(0.99979, 1.00042)
Fluid Film	10	1.00069	0.00018	(1.00038, 1.00100)

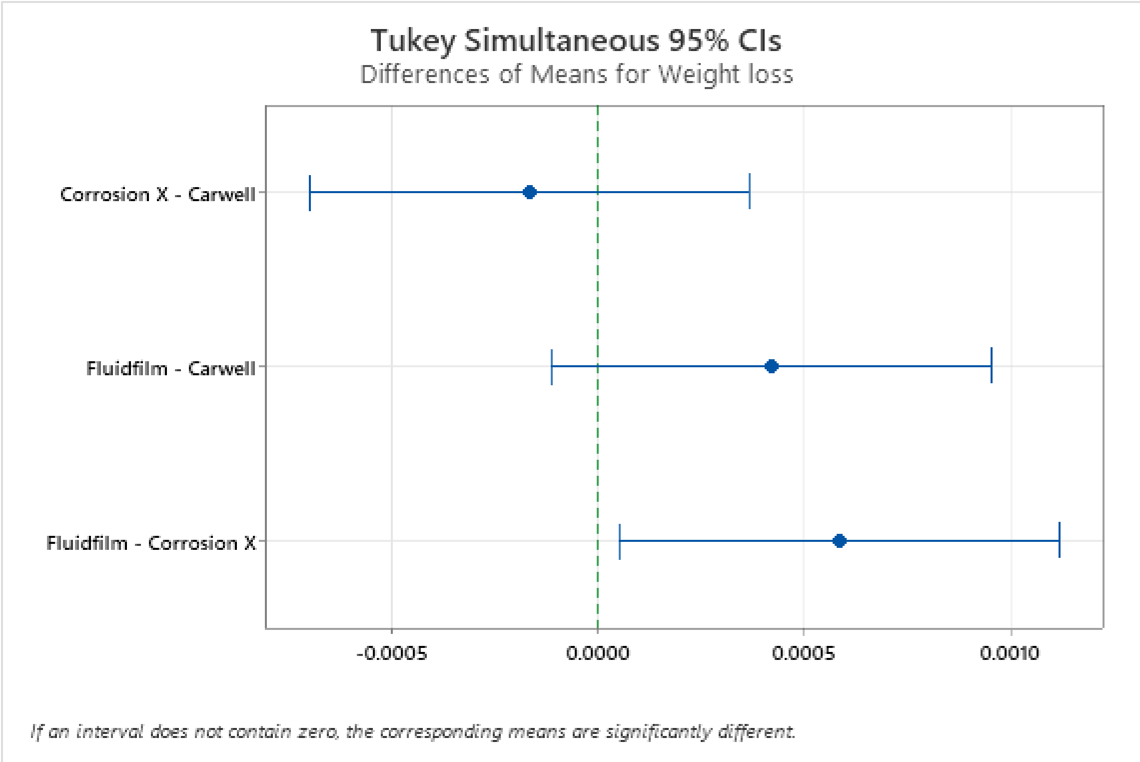
Pooled StDev = 0.000478781

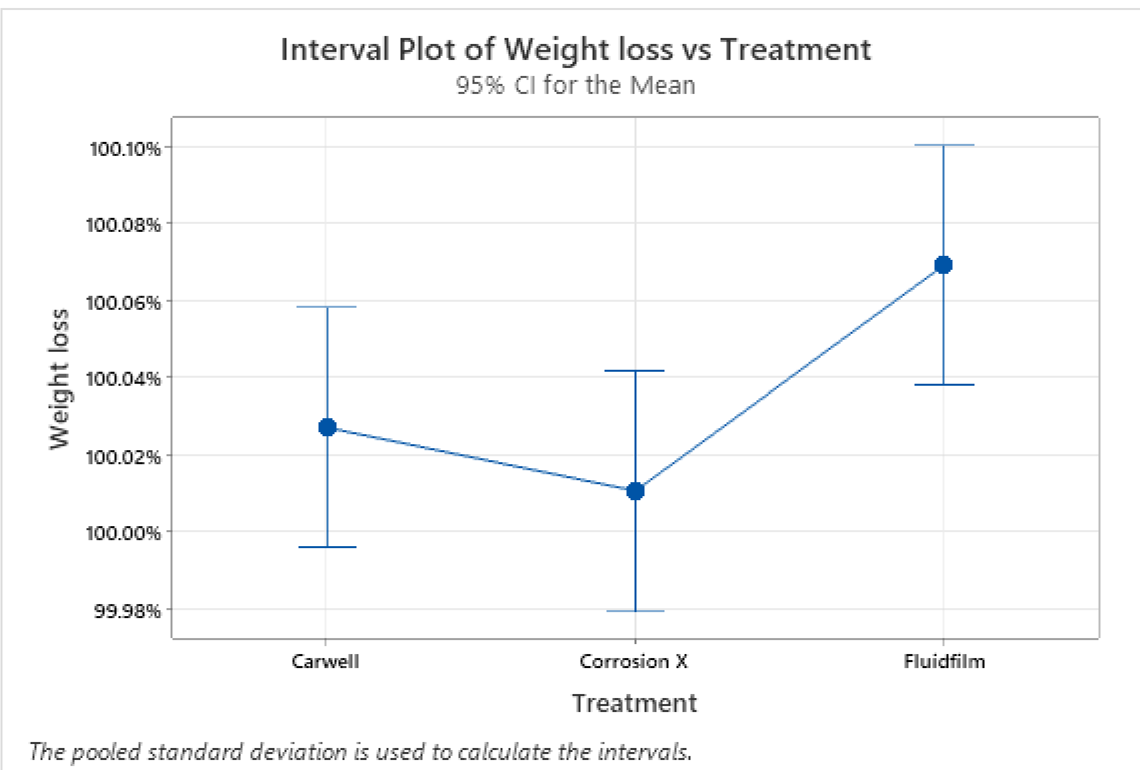
Tukey Pairwise Comparisons

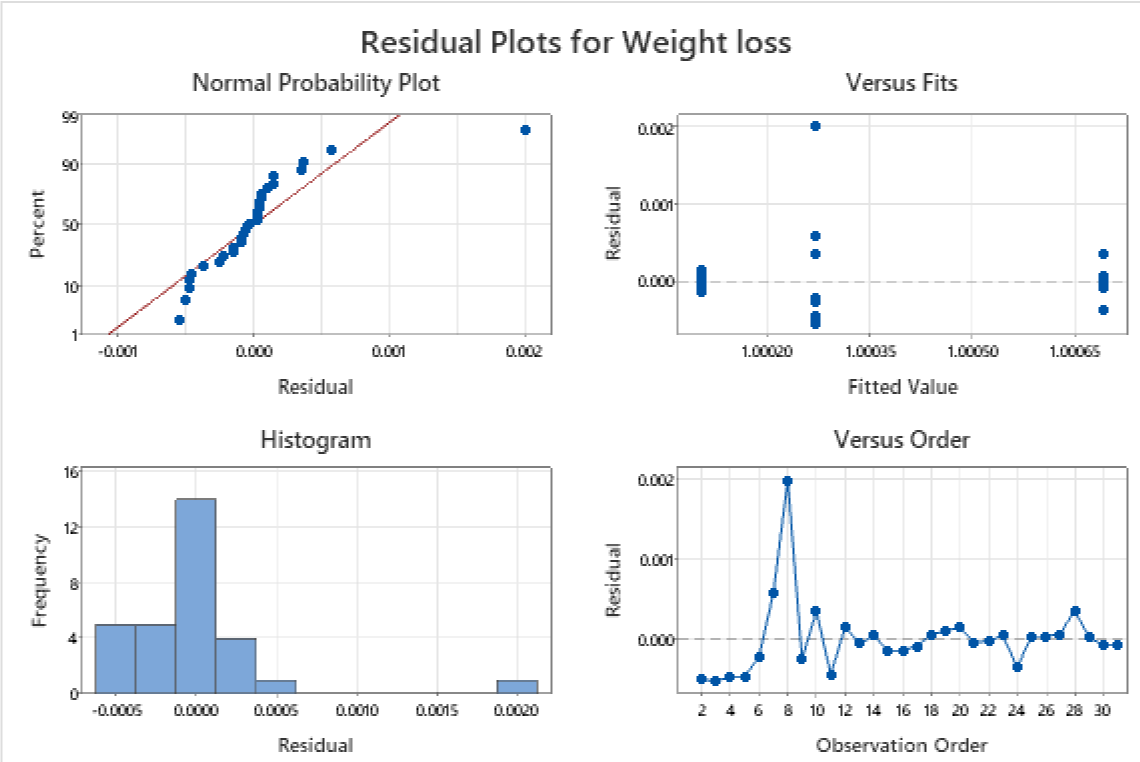
Grouping Information Using the Tukey Method and 95% Confidence

Treatment	N	Mean	Grouping	
Fluid Film	10	1.00069	A	
Carwell	10	1.00027	A	B
Corrosion X	10	1.00011		B

Means that do not share a letter are significantly different.


Tukey Simultaneous 95% CIs
Differences of Means for Weight loss
Corrosion X - Carwell
Fluidfilm - Carwell
Fluidfilm - Corrosion X
-0.0005
0.0000
0.0005
0.0010
If an interval does not contain zero, the corresponding means are significantly different.


Interval Plot of Weight loss vs Treatment
95% CI for the Mean
Weight loss
100.10%
100.08%
100.06%
100.04%
100.02%
100.00%
99.98%
Carwell
Corrosion X
Fluidfilm
Treatment
The pooled standard deviation is used to calculate the intervals.



Residual Plots for Weight loss
Normal Probability Plot
Percent
99
90
50
10
1
-0.001
0.000
0.001
0.002
Residual
Versus Fits
Residual
0.002
0.001
0.000
1.00020
1.00035
1.00050
1.00065
Fitted Value
Histogram
Frequency
16
12
8
4
0
-0.0005
0.0000
0.0005
0.0010
0.0015
0.0020
Residual
Versus Order
Residual
0.002
0.001
0.000
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Observation Order

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APPENDIX F. MINITAB ANALYSIS—TUKEY HSD

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Treatment	4	Carwell, Control, CorrosionX, Fluid Film

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	3	0.000001	0.000000	3.73	0.032
Error	17	0.000002	0.000000		
Total	20	0.000003			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0003063	39.69%	29.05%	3.88%

Means

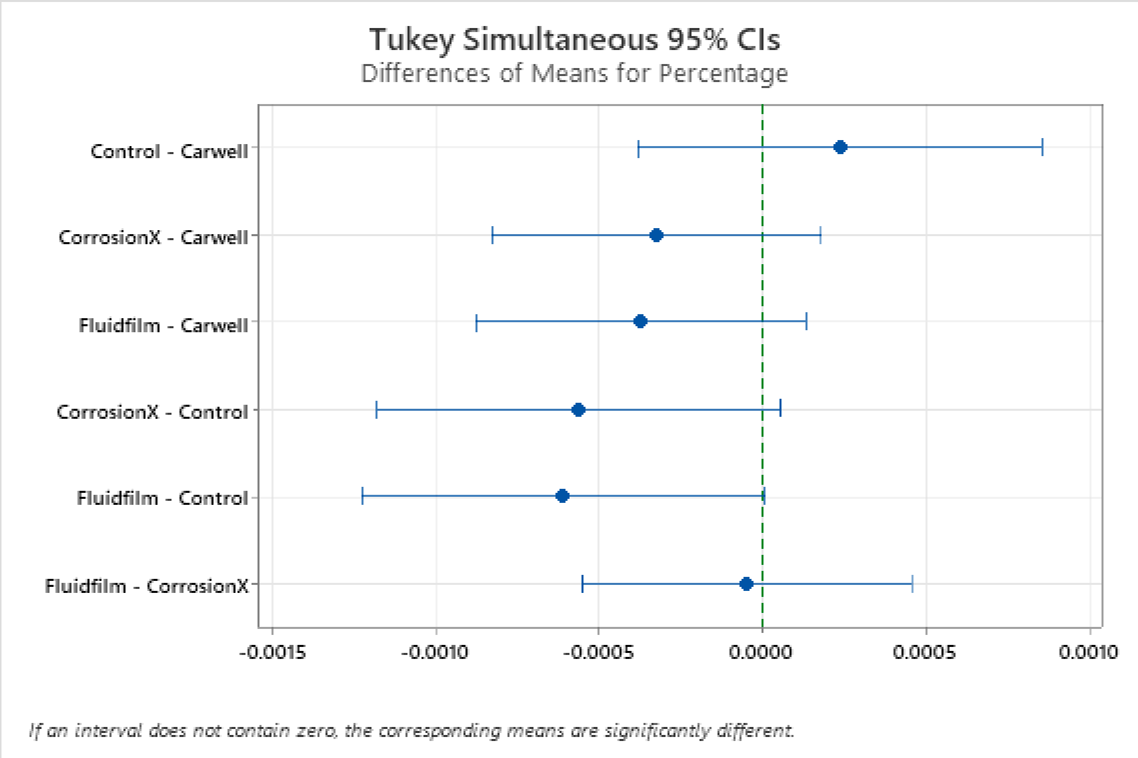
Treatment	N	Mean	StDev	95% CI
Carwell	6	0.001132	0.000302	(0.000868, 0.001395)
Control	3	0.001370	0.000389	(0.000997, 0.001743)
CorrosionX	6	0.000809	0.000355	(0.000545, 0.001073)
Fluid Film	6	0.000762	0.000202	(0.000499, 0.001026)

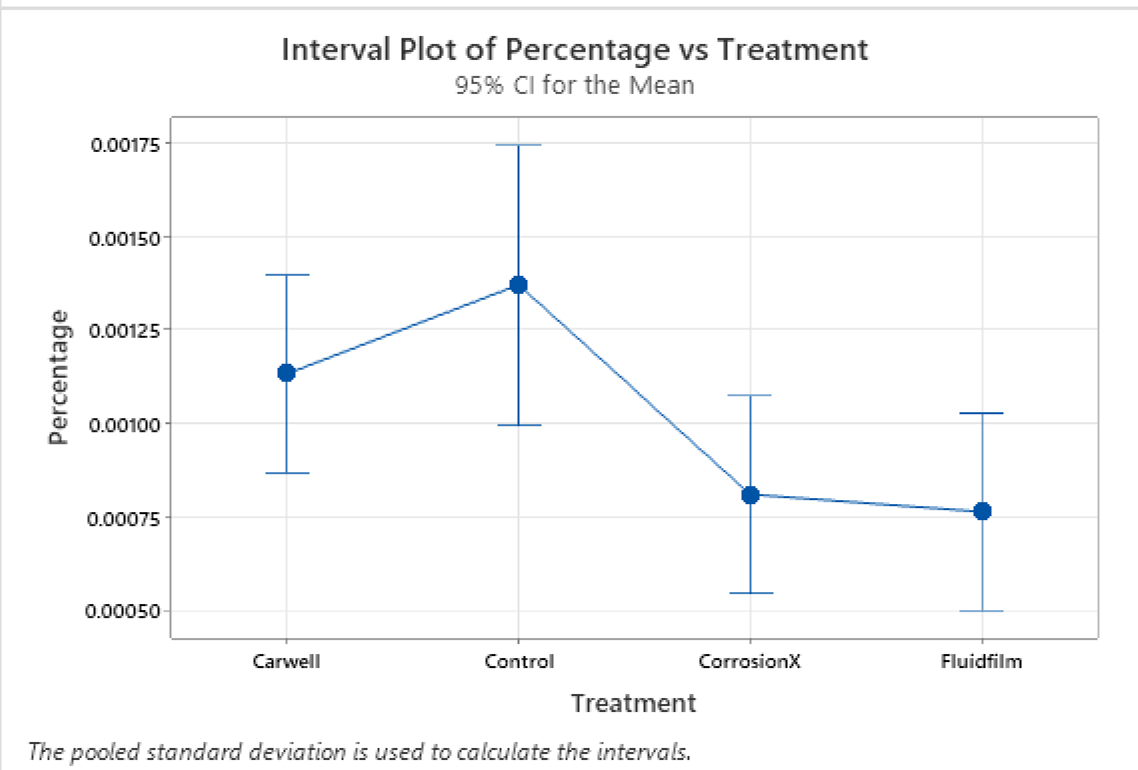
Pooled StDev = 0.000306294

Grouping Information Using the Tukey Method and 95% Confidence

Treatment	N	Mean	Grouping
Control	3	0.001370	A
Carwell	6	0.001132	A
CorrosionX	6	0.000809	A
Fluid Film	6	0.000762	A

Means that do not share a letter are significantly different.





APPENDIX G. FISCHER PAIR WISE COMPARISONS

One-way ANOVA: Percentage versus Treatment

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Treatment	4	Carwell, Control, CorrosionX, Fluid Film

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	3	0.000001	0.000000	3.73	0.032
Error	17	0.000002	0.000000		
Total	20	0.000003			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0003063	39.69%	29.05%	3.88%

Means

Treatment	N	Mean	StDev	95% CI
Carwell	6	0.001132	0.000302	(0.000868, 0.001395)
Control	3	0.001370	0.000389	(0.000997, 0.001743)
CorrosionX	6	0.000809	0.000355	(0.000545, 0.001073)
Fluid Film	6	0.000762	0.000202	(0.000499, 0.001026)

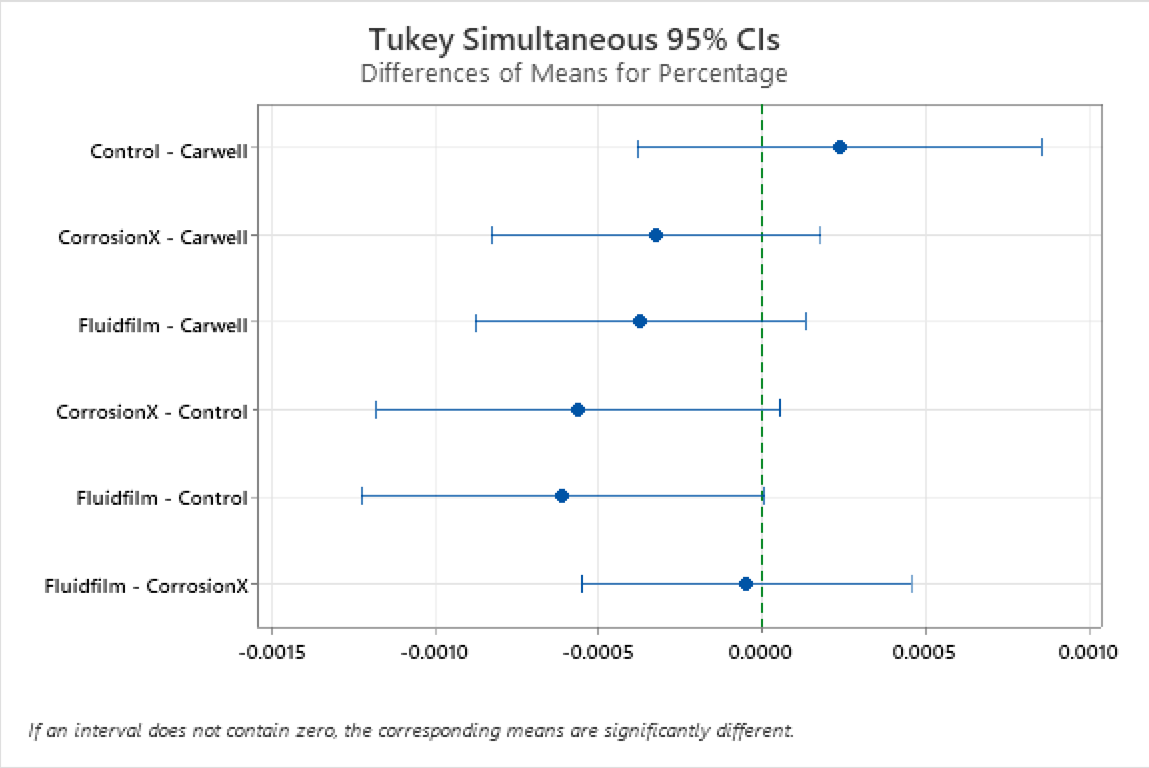
Pooled StDev = 0.000306294

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Treatment	N	Mean	Grouping
Control	3	0.001370	A
Carwell	6	0.001132	A
CorrosionX	6	0.000809	A
Fluid Film	6	0.000762	A

Means that do not share a letter are significantly different.

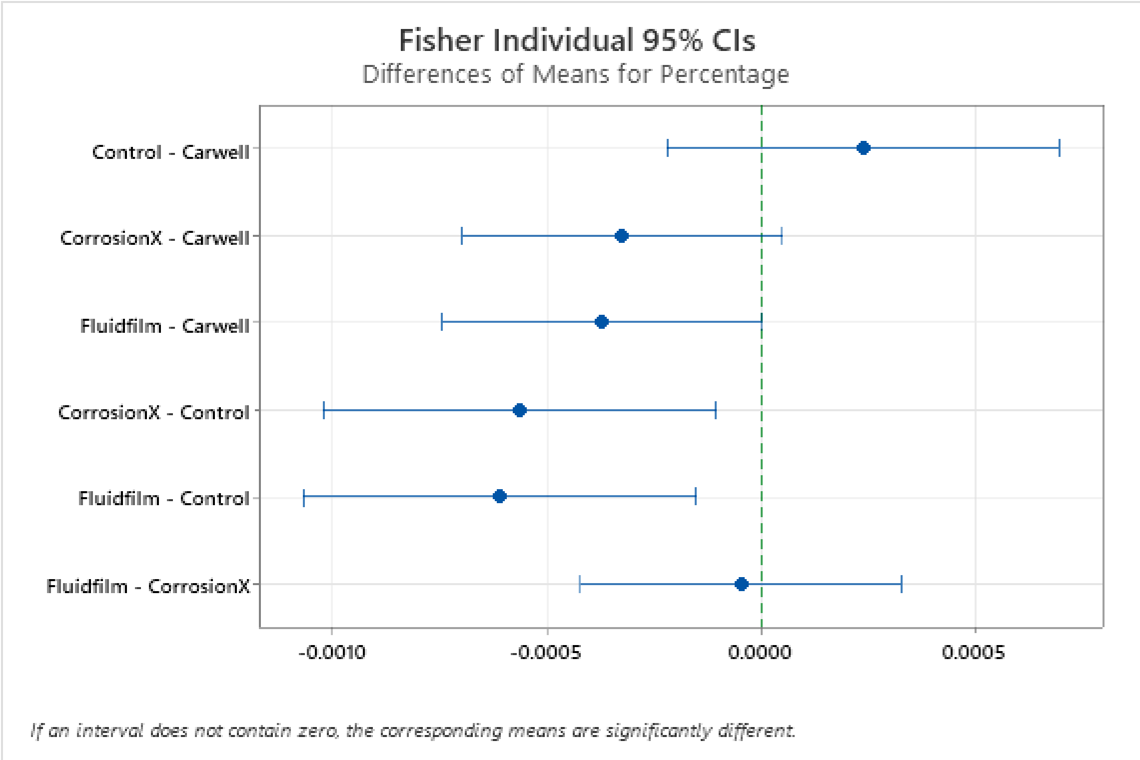


Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Treatment	N	Mean	Grouping	
Control	3	0.001370	A	
Carwell	6	0.001132	A	B
CorrosionX	6	0.000809		B
Fluid Film	6	0.000762		B

Means that do not share a letter are significantly different.

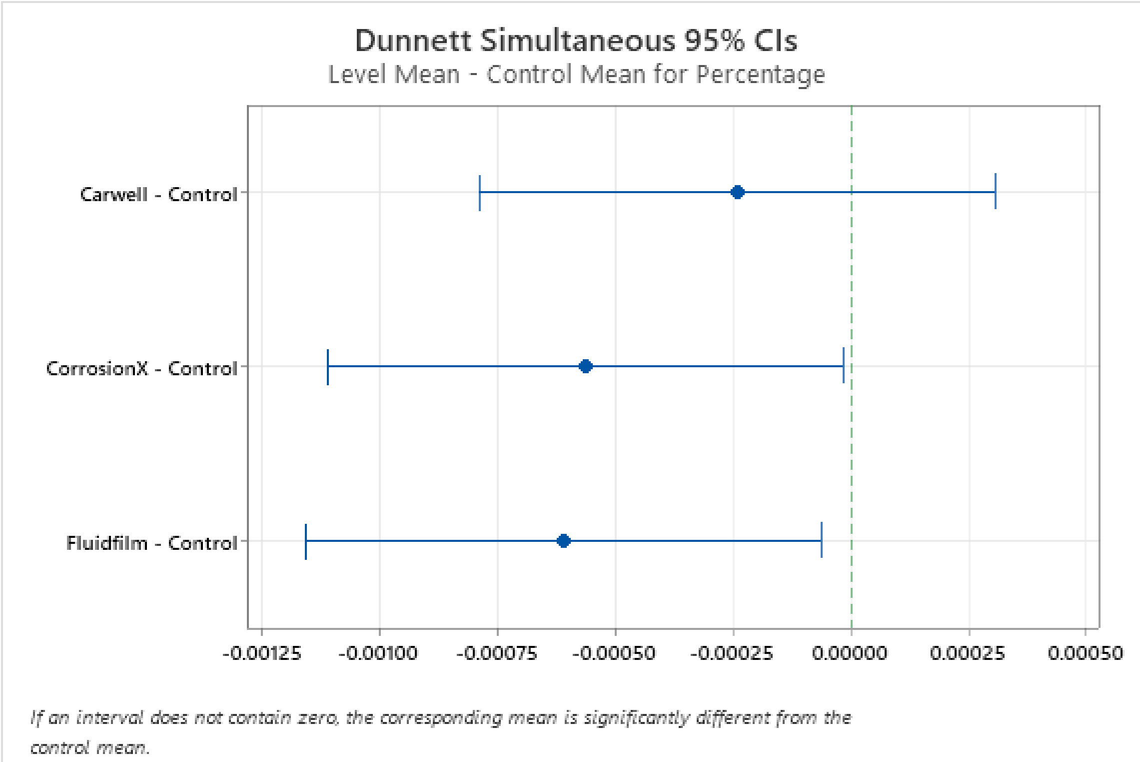


Dunnett Multiple Comparisons with a Control

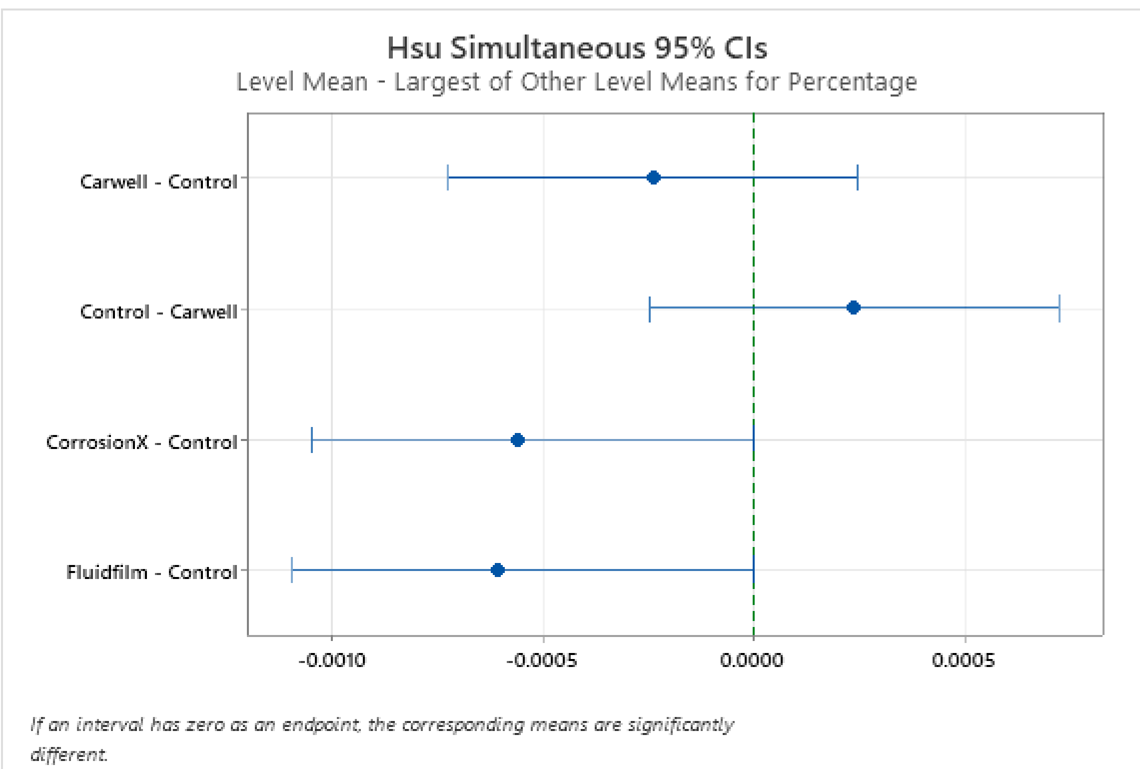
Grouping Information Using the Dunnett Method and 95% Confidence

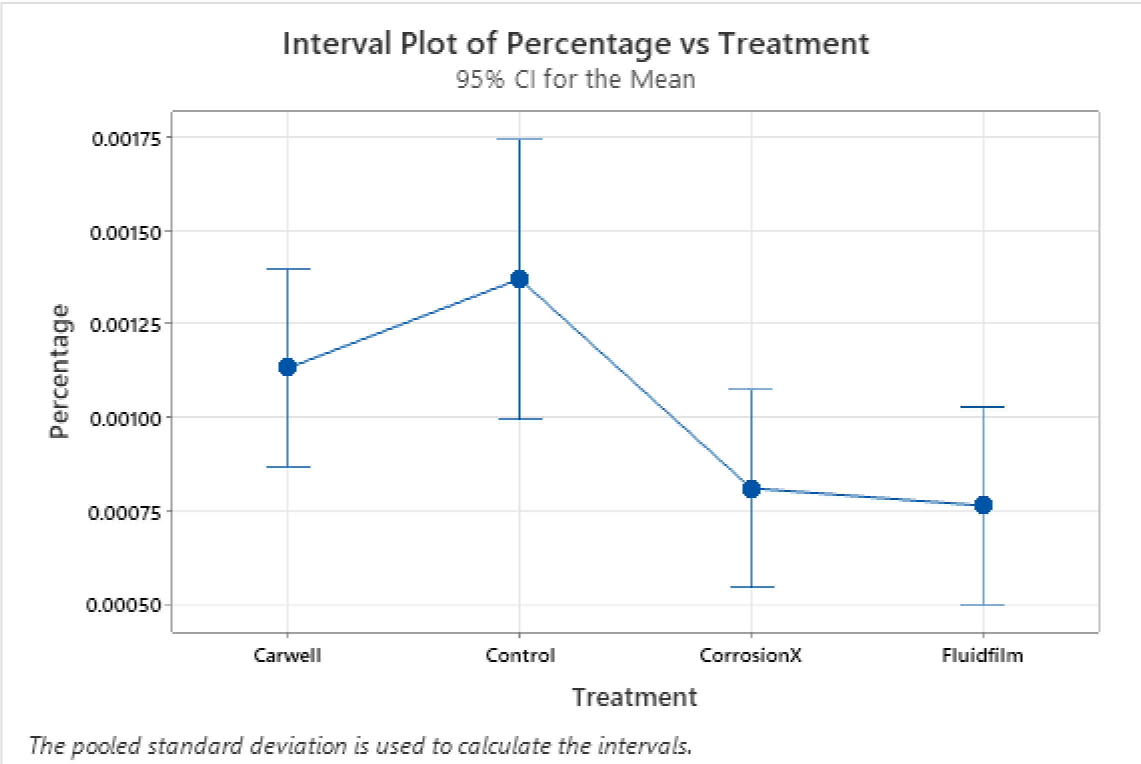
Treatment	N	Mean	Grouping
Control (control)	3	0.001370	A
Carwell	6	0.001132	A
CorrosionX	6	0.000809	
Fluid Film	6	0.000762	

Means not labeled with the letter A are significantly different from the control level mean.



Hsu Multiple Comparisons with the Best (MCB)





Interval Plot of Percentage vs Treatment
95% CI for the Mean
Percentage
0.00175
0.00150
0.00125
0.00100
0.00075
0.00050
Carwell
Control
CorrosionX
Fluidfilm
Treatment
The pooled standard deviation is used to calculate the intervals.

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APPENDIX H. t-TESTS

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = Carwell
μ_2: population mean of Percentage when Treatment = Control
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
Carwell	6	0.001132	0.000302	0.00012
Control	3	0.001370	0.000389	0.00022

Estimation for Difference

Difference	95% CI for Difference
-0.000238	(-0.001054, 0.000578)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-0.93	3	0.421

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = Control
μ_2: population mean of Percentage when Treatment = CorrosionX
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
Control	3	0.001370	0.000389	0.00022
CorrosionX	6	0.000809	0.000355	0.00015

Estimation for Difference

Difference	95% CI for Difference

0.000561	(-0.000291, 0.001412)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
2.10	3	0.127

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = Control
μ_2: population mean of Percentage when Treatment = Fluidfilm
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
Control	3	0.001370	0.000389	0.00022
Fluidfilm	6	0.000762	0.000202	0.000082

Estimation for Difference

Difference	95% CI for Difference
0.000607	(-0.000423, 0.001637)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
2.54	2	0.127

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = Carwell
μ_2: population mean of Percentage when Treatment = CorrosionX
Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
Carwell	6	0.001132	0.000302	0.00012
CorrosionX	6	0.000809	0.000355	0.00015

Estimation for Difference

Difference	95% CI for Difference
0.000322	(-0.000108, 0.000753)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
1.69	9	0.125

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = Carwell

μ_2: population mean of Percentage when Treatment = Fluidfilm

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
Carwell	6	0.001132	0.000302	0.00012
Fluidfilm	6	0.000762	0.000202	0.000082

Estimation for Difference

Difference	95% CI for Difference
0.000369	(0.000027, 0.000711)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
2.49	8	0.038

MINITAB THESIS.MWX

Two-Sample t-Test and CI: Percentage, Treatment

Method

μ_1: population mean of Percentage when Treatment = CorrosionX

μ_2: population mean of Percentage when Treatment = Fluidfilm
Difference: μ_1 - μ_2

Equal variances are not assumed for this analysis.

Descriptive Statistics: Percentage

Treatment	N	Mean	StDev	SE Mean
CorrosionX	6	0.000809	0.000355	0.00015
Fluidfilm	6	0.000762	0.000202	0.000082

Estimation for Difference

Difference	95% CI for Difference
0.000047	(-0.000348, 0.000441)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
0.28	7	0.788

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