Effects of Moisture, Location, and Angle on Automotive Paint System Appearance During Natural Weathering

by Henry K. Hardcastle III
Atlas Material Testing Technology LLC*

Technology Today

This article presents results from a single Design of Experiment (DOE) in natural outdoor weathering. Results show comparative effects of three weathering variables: moisture, exposure angle, and exposure location. The experiment design reveals rank importance of the study variables and links characteristics of the outdoor weathering environment with appearance degradation of coatings. The DOE data follows glass retention of four automotive paint systems over 96 months in subtropical Florida and Texas.

The article discusses some of the root causes and co-variables which may explain automotive paint appearance degradation.

INTRODUCTION AND BACKGROUND

The Moisture Variable

Researchers know moisture plays a key role in weathering of many materials and often place moisture in a set of three primary weathering variables with sunlight and temperature. Researchers use southern Florida as a weathering reference environment because of its relative humidity, rain, condensation, and the important effect moisture plays in weathering. Researchers also make great efforts to include moisture variable control in artificial weathering tests for both simulation and acceleration of natural outdoor weathering degradation.

Moisture represents an important focus for weathering studies, exposure standards, service life predictions.

Presented at the 3rd International Weathering Symposium, Confederation of European Environmental Engineering Societies, September 13-14, 2007, Krakow, Poland.
*56601 N. 470 Ave., Phoenix, AZ 85087-7042.

JCT CoatingsTech
www.coatings.tech

Several recent studies also show the important effect of moisture on material degradation rates and characteristics of automotive coatings. Because of these historic and recent perspectives of moisture's role in degradation of automotive coatings, a research goal was identified to perform a simple weathering experiment designed to help quantify the role of the moisture variable compared to other weathering variables on auto coating degradation. One study objective included using natural outdoor weathering rather than artificial or accelerated methods. Another study objective included tracking long-term degradation (longer than five years outdoor weathering) in order to characterize the naturally occurring long-term appearance degradation pattern, rather than only the initiation portion of the degradation function. In 1998, researchers planned a simple DOE to meet these objectives and began exposure and measurement of commercially available automotive paint systems. This simple study illustrates the important and powerful role moisture can have on weathering degradation rates and underlines the care and consideration researchers need to use to incorporate the moisture variable into experiments and tests aimed at predicting material end-use outdoor performance.

The DOE Approach to Weathering Experiments

Traditional natural outdoor weathering studies ordinarily consist of simple exposures of material specimens in outdoor environments for periods of time while making miscellaneous measurements of material characteristics throughout the exposure. Sometimes the measured characteristic (also known as "output variable" or "dependent variable") is graphed on a y-axis with some appropriate measurement of exposure duration on the x-axis to form a curve or degradation function. These exposure trials are typically observational in nature as researchers do not try to influence the naturally occurring environmental variables (also known as "input variables" or "independent variables"), causing the degradation.

Sometimes researchers construct actual experiments using these outdoor exposure trials. An example may be when a researcher considers different additives or amounts of a single additive in a system to promote outdoor weathering durability. The researcher sets up an experiment subjecting specimens with varying types or amounts of additives to an outdoor weathering exposure trial. Degradation curves can then be analyzed to assess the best additive or best amount. In this style of experiment, the research is controlling the material variable. The additive type or amount represents the independent variable controlled by the researcher. The researcher usually does not control environmental variables as part of this type of weathering experiment and, consequently, gathers no information on how changing environmental factors affect the degradation characteristics.

More recently, weathering researchers have begun considering effects of environmental variables on degradation characteristics by performing experiments on standard specimens while varying environmental factors in artificial weathering devices to determine how different levels of an environmental factor (the independent variable in this case) affects a degradation function. For example, an experiment may expose standard specimens to different relative humidity levels while holding other variables constant (such as spectral power distribution, irradiance level, temperature, etc.). Typically, these experiments vary only one environmental factor at a time under artificially controlled conditions. This approach is sometimes known as an "OFAT" (one-factor-at-a-time) experiment.

The OFAT approach to natural outdoor weathering research is extremely difficult to perform correctly. It is realistically impossible to only vary one environmental factor at a time in a natural outdoor exposure. Therefore, OFAT experiments typically utilize artificial weathering devices to only vary a single independent weathering variable while holding other factors constant. Natural outdoor environments, however, never generate single factor variation while other factors remain constant. The phrase "n-dimensional hypervolume" underscores the dynamic multi-variable outdoor environment's interaction with materials. Likewise, for this reason, single OFAT weathering experiments can be considered highly artificial and over-simplistic constructs offering only meager information relating back to material performance in the natural outdoor weathering environment hypersurface. OFAT experiments simply do not have the power to characterize weathering processes occurring in the n-dimensional hypervolume of the natural weathering environment. DOE approaches, therefore, do.

"Design of Experiments (DOE) is the simultaneous study of several process variables. By combining several variables in one study instead of creating a separate study for each, the amount of testing required will be drastically reduced and greater process understanding will result. This is in direct contrast to the typical one-factor-at-a-time approach or OFAT which limits the understanding and wastes data. Additionally, OFAT studies cannot be assured of detecting the unique effects of combinations of factors (a condition to be later defined as an interaction)."*

A weathering DOE, therefore, is simply a traditional DOE which varies several weathering factors (variables) simultaneously to characterize the effects of individual factors and their interactions on the study material. DOEs include two types: fractional factorial (sometimes called screening experiments) and full factorial
Effects of Moisture, Location, and Angle on Automotive Paint System Appearance During Natural Weathering

by Henry K. Hardcastle III
Atlas Material Testing Technology LLC

This article presents results from a single Design of Experiment (DOE) in natural outdoor weathering. Results show comparative effects of three weathering variables: moisture, exposure angle, and exposure location. The experiment design reveals rank importance of the study variables and links characteristics of the outdoor weathering environment with appearance degradation of coatings. The DOE data follows glass retention of four automotive paint systems over 96 months in subtropical Florida and Arizona. The article discusses some of the root causes and co-variables which may explain automotive paint appearance degradation.

Introduction and Background

The Moisture Variable

Researchers know moisture plays a key role in weathering of many materials and often place moisture in a set of three primary weathering variables with sunlight and temperature. Researchers use southern Florida as a weathering reference environment because of its relative humidity, rain, condensation, and the important effect moisture plays in weathering. Researchers also make great efforts to include moisture variable control in artificial weathering tests for both simulation and acceleration of natural outdoor weathering degradation.

Moisture represents an important focus for weathering studies, exposure standards, service life prediction, methodology, and weathering device design. Several recent studies also show the important effect of moisture on material degradation rates and characteristics of automotive coating systems.6-7 Because of these historic and recent perspectives of moisture's role in degradation of automotive coatings, a research goal was identified to perform a simple weathering experiment designed to help quantify the role of the moisture variable compared to other weathering variables on auto coating degradation. One study objective included using natural outdoor weathering rather than artificial or accelerated methods. Another study objective included tracking long-term degradation (longer than five years outdoor weathering) in order to characterize the naturally occurring long-term appearance degradation pattern, rather than only the initiation portion of the degradation function. In 1998, researchers planned a simple DOE to meet these objectives and began exposure and measurement of commercially available automotive paint systems. This simple study illustrates the important and powerful role moisture can have on weathering degradation rates and underlines the care and consideration researchers need to use to incorporate the moisture variable into experiments and tests aimed at predicting material end-use outdoor performance.

The DOE Approach to Weathering Experiments

Traditional natural outdoor weathering studies ordinarily consist of simple exposures of material specimens in outdoor environments for periods of time while making intermittent measurements of material characteristics throughout the exposure. Sometimes the measured characteristic (also known as "output variable" or "dependent variable") is graphed on a y-axis with some appropriate measurement of exposure duration on the x-axis to form a curve or degradation function. These exposure trials are typically observational in nature as researchers do not try to influence the naturally occurring environmental variables (also known as "input variables" or "independent variables").

Some times researchers construct actual experiments using these outdoor exposure trials. An example may be when a researcher considers different additives or amounts of a single additive in a system to promote outdoor weathering durability. The researcher sets up an experiment subjecting specimens with varying types or amounts of additives to an outdoor weathering exposure trial. Degradation curves can then be analyzed to assess the best additive or best amount. In this style of experiment, the researcher is controlling the material variable. The additive type or amount represents the independent variable controlled by the researcher. The researcher usually does not control environmental variables as a part of this type of weathering experiment and, consequently, gathers no information on how changing environmental factors affect the degradation characteristics.

More recently, weathering researchers have begun considering effects of environmental variables on degradation characteristics by performing experiments on standard specimens while varying environmental factors in artificial weathering devices to determine how different levels of an environmental factor (the independent variable in this case) affects a degradation function. For example, an experiment may expose standard specimens to different relative humidity levels while holding other variables constant (such as spectral power distribution, irradiance level, temperature, etc.). Typically, these experiments vary only one environmental factor at a time under artificially controlled conditions. This approach is sometimes known as an "OFAT" (one-factor-at-a-time) experiment.

The OFAT approach to natural outdoor weathering research is extremely difficult to perform correctly. It is realistically impossible to only vary one environmental factor at a time in a natural outdoor exposure.

Therefore, OFAT experiments typically utilize artificial weathering devices to only vary a single independent weathering variable while holding other factors constant. Natural outdoor environments, however, never generate single factor variation while other factors remain constant! The phrase "n-dimensional hypervolume" underscores the dynamic multi-variable outdoor environment's interaction with materials. Likewise, for this reason, single OFAT weathering experiments can be considered highly artificial and over-simplistic constructs offering only meager information relating back to material performance in the natural outdoor weathering environment hypervolume. OFAT experiments simply do not have the power to characterize weathering processes occurring in the n-dimensional hypervolume of the natural weathering environment. DOE approaches, however, do.

"Design of Experiments [DOE] is the simultaneous study of several process variables. By combining several variables in one study instead of creating a separate study for each, the amount of testing required will be drastically reduced and greater process understanding will result. This is in direct contrast to the typical one-factor-at-a-time approach or OFAT which limits the understanding and wastes data. Additionally, OFAT studies cannot be assured of detecting the unique effects of combinations of factors (a condition to be later defined as an interaction)."9

A weathering DOE, therefore, is simply a traditional DOE which varies several weathering factors (variables) simultaneously to characterize the effects of individual factors and their interactions on the study material. DOE's include two types: fractional factorial (sometimes called screening experiments) and full factorial.
DOEs. Researchers typically use fractional factorial experiments to narrow a collection of many suspect variables down to a few significant variables and identify the variables that warrant further investigation while screening out variables that do not. Once identified in screening approaches, full factorial DOEs then can be performed for robust characterization of the main effects and interactions of the few key variables. For this study, the screening experiments were presented in separate publications. 10,12

Design and implementation of DOEs using natural weathering factors may present considerable difficulties in natural environments. The power and efficiency of weathering DOE approaches, however, often outweigh these difficulties and justify using weathering DOE approaches.

DESIGN OF EXPERIMENT

Researchers planned a simple natural weathering DOE to help understand the effects of moisture on gloss degradation of automotive coatings. The study objectives included obtaining information which compared the effects of moisture to other weathering factors: exposure location and exposure angle. These three variables—moisture, exposure location, and exposure angle—naturally fit into a 2\(^3\) full factorial DOE. Figure 1 shows this weathering DOE modified from Montgomery. 12

Weathering DOE Trials

This DOE included eight long-term weathering exposures varying the three factors (moisture, exposure angle, and location) simultaneously. The experiment design varied the three factors in an orthogonally balanced manner. Contrasting trials varied each factor to a low (L) and high (H) setting independently of the other factor settings. All eight exposures began within three days of November 20, 1996, and continued throughout the 96 months reported here within. Every three months, the exposed automotive coating specimens were measured and the measurements were plotted against exposure time in order to obtain the degradation curves for each of the eight exposures. In this manner, the DOE characterized the long-term weathering degradation for each variable setting. All specimens were exposed in the backed condition.

Exposure and Independent Variables

Varying independent environmental factors in a natural outdoor weathering experiment may seem paradoxical. "Controlling" a natural environment makes it un-natural. For example, it would be difficult to perform a DOE that actually controlled the temperature of exposed specimens using heating elements while still maintaining the natural cyclic temperature patterns found in outdoor exposures. Still, opportunities exist to control some variables in outdoor exposure without introducing artificial or unnatural weathering conditions. In this DOE, the design achieved control over two factors without introducing artificial and unnatural environments: the exposure angle and exposure location factor. The third factor—moisture—required an artificial application of moisture spray.

The Moisture Variable

In order to characterize the effect of moisture in this DOE, four of the eight trials exposed specimens on racks oriented 45° from the horizontal facing true south while four trials exposed specimens on racks oriented at 90° from the horizontal. Trials shown in Figure 1 with the angle variable set high (+) exposed specimens on racks set at 45° while trials with the angle variable set low (−) exposed specimens on racks set at 90°. This represents an example of controlling a variable in a natural weathering DOE without introducing an artificial effect. In this way, the DOE characterized the effect of changing the exposure angle (and all co-variables associated with exposure angle) on the degradation curves of the auto paint systems.

It is interesting to consider some of the co-variables associated with exposure angle. Radiant exposure (sometimes referred to as "dose") represents one co-variable associated with exposure angle. Cosine effects vary solar intensities and accumulated radiation with changing exposure angle. Figures 3 and 4 show this effect of the total solar radiant exposure and total ultraviolet radiant exposure respectively during the experiment.

Exposures at 45° in Arizona accumulated total solar radiant exposure (dose) slightly faster than at the 90° exposure angle. The 34° latitude of the Arizona exposure site is closer to the 45° exposure angle than the 90° exposure angle under the relatively clear Arizona sky and accounts for the faster rate (see Figure 3).

Figure 1—The 2\(^3\) factorial design weathering experiment.

Figure 2—Approximate cumulative time of wetness.

Figure 3—Arizona and Florida total solar radiant exposure.

Figure 4—Arizona and Florida total ultraviolet radiant exposure.

On the other hand, observations in southern Florida show little differences in total solar radiant exposure between 45° and 90° exposure angles. The 26° North latitude exposure location is close to the median between summer and winter solstice in southern Florida. Additionally, a much more diffuse sky dome in southern Florida (compared to Arizona) may help average direct and diffuse total solar radiant exposure, as shown in Figure 4. Exposures at 5° in Arizona accumulated UV (ultraviolet) radiant exposure (dose) faster than at the 45° exposure angle in Arizona. Specimens exposed at 3° were more of the north sky dome than specimens exposed at 45°. Diffuse UV energy reflects from aerosol particles in the northern part of the sky dome back to specimens exposed at 5°. This diffuse light scattering effect is more pronounced for shorter wavelengths (UV) and explains why the earth's sky appears blue. For the same reasons, the sky dome becomes nearly white when looking up in the northern sky at night.
DOEs. Researchers typically use fractional factorial ex-
periments to narrow a collection of many suspect vari-
able down to a few significant variables and identify
the variables that warrant further investigation while
screening out variables that do not. Once identified in
screening approaches, full factorial DOEs then can be
performed for robust characterization of the main ef-
fects and interactions of the few key variables. For this
study, the screening experiments were presented in sep-
arate publications.10,11

FIGURE 1—The 2^5 factorial design weathering experiment.

FIGURE 2—Approximate cumulative time of weathering.

Design and implementation of DOEs using natural
weathering factors may present considerable difficulties in
natural environments. The power and efficiency of weath-
ing DOE approaches, however, often outweigh these
difficulties and justify using weathering DOE approaches.

DESIGN OF EXPERIMENT

Researchers planned a simple natural weathering DOE
to help understand the effects of moisture on
gloss degradation of automotive coatings. The study
objectives included obtaining information which com-
pared the effects of moisture to two other weathering
factors: exposure location and exposure angle. These
three variables—moisture, exposure location, and expo-
sure angle—naturally fit into a 2^5 full factorial DOE.

Weighing DOE Trials

This DOE included eight long-term weathering explo-
sions varying the three factors (moisture, exposure an-
gle, and location) simultaneously. The experiment de-
sign varied the three factors in an orthogonally
balanced manner. Contrasting trials varied each factor
to a low (−1) and high (+1) setting independently of
the other factor settings. All eight exposures began within
three days of November 20, 1996, and continued
throughout the 96 months reported herein. Every
three months, the exposed automotive coating speci-
mens were measured and the measurements were plot-
ted against exposure time in order to obtain the degra-
dation curves for each of the eight exposures. In this
manner, the DOE characterized the long-term weather-
ning degradation for each variable setting. All specimens
were exposed in the backed condition.

EXPOSURE AND INDEPENDENT VARIABLES

Varying independent environmental factors in a nat-
ural outdoor weathering experiment may seem para-
doxical. "Controlling" a natural environment makes it
un-natural. For example, it would be difficult to per-
form a DOE that actually controlled the temperature of
exposed specimens using heating elements while still
maintaining the natural cyclic temperature patterns
found in outdoor exposures. Still, opportunities exist
to control some variables in outdoor exposure without
introducing artificial or unnatural weathering condi-
tions. In this DOE, the design achieved control over
two factors without introducing artificial and unnatu-
ral environments: the exposure angle and exposure lo-
cation factor. The third factor—moisture—required an
artificial application of moisture spray.

The Moisture Variable

In order to characterize the effect of moisture in this
DOE, four of the eight trials exposed specimens on
racks oriented 45° from the horizontal facing true
south while four trials exposed specimens on racks ori-
teared at 90° from the horizontal. Trials shown in Figure
1 with the angle variable set high (+1) exposed speci-
mens on racks set at 45° while trials with the angle vari-
able set low (−1) exposed specimens on racks set at 45°.
This represents an example of controlling a variable in
a natural weathering DOE without introducing an arti-
ficial effect. In this way, the DOE characterized the ef-
fect of changing the exposure angle (and all co-vari-
ables associated with exposure angle) on the degra-
dation curves of the auto paint systems.

It is interesting to consider some of the co-variables
associated with exposure angle. Radiant exposure
(sometimes referred to as dose) represents one co-vari-
able associated with exposure angle. Cosine effects vary
solar intensities and accumulated radiation with chang-
ing exposure angle. Figures 3 and 4 show this effect of
the total solar radiant exposure and total ultraviolet ra-
diant exposure respectively during the experiment.

Exposures at 45° in Arizona accumulated total solar
radiant exposure (dose) slightly faster than at the 5°
exposure angle. The 34° latitude of the Arizona expo-
sure site is closer to the 45° exposure angle than the 5°
exposure angle under the relatively clear Arizona sky
and accounts for the faster rate (see Figure 3).

CONCLUSION

The DOE experiment comprised a 2^5 full factorial
DOE designed to characterize the effects of
moisture, exposure angle, and exposure location on
the gloss degradation of automotive coatings. The ex-
periment was designed to compare and contrast three
factors: moisture, exposure angle, and exposure loca-
tion. A spray nozzle applied high purity de-ionized
water to specimens exposed on spray racks. A single
spray event lasted 60 sec. Eight spray events occurred
at the beginning of each hour from 08:00 hr until 16:00
hr during each day of the exposure. Trials shown in
Figure 1 with the moisture spray variable set high (+1)
exposed specimens on spray racks while trials with the
moisture spray variable set low (−1) exposed specimens
on racks with no spray. In this way, the DOE character-
ized the effect of an artificially introduced moisture
spray on the weathering degradation of the auto paint
systems.

It is interesting to consider some of the co-variables
associated with the moisture spray factor in this ex-
periment. The eight controlled one-minute sprays represent
one source of the moisture in this experiment.

However, another important source of moisture co-
varyes with the location factor and the angle factor.

On the other hand, observations in southern Florida
show little differences in total solar radiant exposure
between 5° and 45° exposure angles. The 26° North
latitude exposure location is close to the median be-
tween summer and winter solstice in southern Florida.
Additionally, a much more diffuse sky dome in south-
ern Florida (compared to Arizona) may help average
direct and diffuse total solar radiant exposure, as
shown in Figure 3.

Exposures at 5° in Arizona accumulated UV (ultra-
viiolet) radiant exposure (dose) faster than at the 45°
exposure angle in Arizona. Specimens exposed at 5° are
more of the north sky dome than specimens exposed at
45°. Diffuse UV energy reflects from aerosol particles
in the north part of the sky dome back to specimens
exposed at 5°. This diffuse light scattering effect is
more pronounced for shorter wavelengths (UV) and
explains why the earth's sky appears blue. For the same

46 January 2008

JCT CoatingsTech
reason, 5° UV radiant exposure in southern Florida accumulates faster than the 45° UV radiant exposure in southern Florida (see Figure 4).

The Exposure Location Variable

In order to characterize the effect of exposure location in this DOE, four of the eight trials exposed specimens in southern Florida while the other four trials exposed specimens in desert Arizona. Trials shown in Figure 1 with the location variable set high (+) exposed specimens at Atlas Material Testing Technology’s South Florida outdoor site located at 25° 47’ North latitude, 80° 50’ West longitude, while trials with the location variable set low (−) were exposed at Atlas Material Testing Technology’s central Arizona outdoor site located at 33° 54’ North latitude, 112° 81’ West longitude. This represents another example of controlling a variable in a natural weathering DOE without introducing artificial effects. In this way, the DOE characterized the effect of changing the exposure location (and all co-variables associated with these locations) on the degradation curves.

By changing exposure variables in this manner, the DOE obtained the following sets of weathering exposure information: four trials with water spray, four trials without water spray, four trials exposed at 5° angle, four trials exposed at 45° angle, four trials exposed in Florida, and four trials exposed in Arizona (for a total of 24 trials worth of data) by only actually performing eight trials. This power and efficiency of orthogonally balanced DOE trials represents one reason DOE approaches are especially suitable for weathering experiments. It is important to remember, however, that while researchers may control input variables for natural weathering DOEs, the natural environment may also affect study variables. Researchers must utilize considerable experience and skill to understand the interplay between effects caused by man and effects caused by nature in the environment within which the experiment is being performed.

MATERIALS AND DEPENDENT VARIABLES

Automotive Paint Systems

Within each exposure trial, the DOE exposed four “replicates” of commercially available automotive paint specimens. Each of the four replicates had the same formulation of acrylic melamine clear topcoat. Each of the four replicates had a different color basecoat: red, yellow, green, and blue. Each of the replicates came from a different manufacturing batch of specimens. By introducing some variation into the specimens via different color basecoats and manufacturing batches, the DOE captured information about the effect of this variation on the clearcoat performance and compared the effects of replicate variation (as experiment error) to the effects of the study variables (moisture spray, angle, and location). Additionally, the DOE captured information on the effects of the study variables across several different colors of paint system rather than limit interpretation of results to only a single color. The screening experiment publication fully describes the clearcoats exposed in this experiment.13

Figure 13—Main effects contrasts.
The Exposure Location Variable

In order to characterize the effect of exposure location in this DOE, four of the eight trials exposed specimens in southern Florida while the other four trials exposed specimens in desert Arizona. Trials shown in Figure 1 with the location variable set high (+) exposed specimens at Atlas Material Testing Technology’s South Florida outdoor site located at 25° 47’ North latitude, 86° 50’ West longitude, while trials with the location variable set low (-) were exposed at Atlas Material Testing Technology’s central Arizona outdoor site located at 33° 54’ North latitude, 112° 81’ West longitude. This represents another example of controlling a variable in a natural weathering DOE without introducing artificial effects. In this way, the DOE characterized the effect of changing the exposure location (and all co-variables associated with these locations) on the degradation curves.

By changing exposure variables in this manner, the DOE obtained the following sets of weathering exposure information: four trials with water spray, four trials without water spray, four trials exposed at 5° angle, four trials exposed at 45° angle, four trials exposed in Florida, and four trials exposed in Arizona (for a total of 24 trials worth of data) by only actually performing eight trials. This power and efficiency of orthogonally balanced DOE trials represents one reason DOE approaches are especially suitable for weathering experiments. It is important to remember, however, that while researchers may control input variables for natural weathering DOEs, the natural environment may also affect study variables. Researchers must utilize considerable experience and skill to understand the interplay between effects caused by man and effects caused by nature in the environment within which the experiment is being performed.

MATERIALS AND DEPENDENT VARIABLES

Automotive Paint Systems

Within each exposure trial, the DOE exposed four "replicates" of commercially available automotive paint specimens. Each of the four replicates had the same formulation of acrylic melamine clear topcoat. Each of the four replicates had a different color basecoat: red, yellow, green, and blue. Each of the replicates came from a different manufacturing batch of specimens. By introducing some variation into the specimens via different color basecoats and manufacturing batches, the DOE captured information about the effect of this variation on the clearcoat performance and compared the effects of replicate variation (as experiment error) to the effects of the study variables (moisture spray, angle, and location). Additionally, the DOE captured information on the effects of the study variables across several different colors of paint system rather than limit interpretation of results to only a single color. The screening experiment publication fully describes the clearcoats exposed in this experiment.13

Figure 13—Main effects contrasts.
Appearance Measurements

Gloss represents an important characteristic of automotive paint systems and the auto industry widely studies gloss weathering degradation of automotive coatings. Technicians performed $20^\circ$ gloss measurements on each replicate of each trial every three months in accordance with ASTM D 523-89. Since the results and analysis did not show any analytical advantage by using delta gloss or percent gloss loss, this report presents actual measured gloss values. The same type of clear coating on the different replicates showed approximately the same initial values. Technicians measured gloss at the two different exposure locations using the same model gloss meters and identical measurement procedures including frequent calibrations during measurements.

RESULTS AND ANALYSIS

Figures 5 through 12 show the results of the eight trials in this weathering DOE as the degradation curves, through 96 months of exposure. Gloss measurements were not performed on the specimens until 30 months after the exposures started. Some of the curves show a portion of the function indicative of rate dependent degradation (slope) followed by a leveling off of the curve once some level of degradation had been achieved. Because of this characteristic of the degradation curves, analysis of the data at different points in time can drastically affect the results. For example, analyzing data after all the trial specimens have completely degraded will show no effects of the study variables. For this reason, the DOE included analysis at two points in the exposure period before the degraded condition had been reached in all the trials. Having the degradation curves to visually inspect, the 45- and 60-month intervals were chosen for analysis.

DOE is primarily a logic tool. The logic includes comparing or contrasting the set of trials with the specific factor of interest set low to the set of trials with the same factor set high. Figure 13, adapted from Montgomery, illustrates this logic for this weathering DOE. The analysis calculates the effect of factor A (spray) by determining an average of the four trials with no spray (low, A-) and evaluating the average of the four trials with spray (high, A+). The analysis uses the same procedure to calculate the effect of factor B (angle), but, contrasts different sets of trials to determine the effect of angle. The analysis contrasts factor C (location) along a third axis of the experimental volume. In this manner, the analysis reveals information regarding the effects of each variable, as well as interactions in a robust manner from only eight trials in this experiment.

The mechanics of DOE analysis are fairly standardized and widely published. The Barrentine reference fully documents the analytical procedures used in this study. The analysis tables in Figure 14 for 45 months and Figure 15 for 60 months follow Barrentine's approach very closely.

OBSERVATIONS

Observations at the 45-Month Interval

The analysis reveals several critical observations shown in Figure 14. Spray (A) had by far, the largest effect on the gloss. Location (C) also showed a significant effect. Angle (B) showed only a marginal effect. Spray (A) interacted significantly with location (C). Spray did not affect gloss degradation in southern Florida as it did in Arizona. A similar interaction also appeared between spray (A) and angle (B). The analy-
The results of the interaction effects for 60 months are graphed in Figure 17, showing the interaction between the spray (A) and location (B) factors in this experiment.

CONCLUSIONS AND CONSIDERATIONS

Natural weathering DOE's offer an efficient and robust approach to characterizing natural weathering material degradation.

Application of only eight daytime moisture sprays of one-minute duration showed significant and important effects on the degradation curves of the automotive paint systems exposed in both Arizona and Florida.

Application of water sprays dramatically accelerated gloss loss and the effect of these moisture sprays far outweighed the effects due to location and exposure angle.

The significant differences in radiant exposure due to different exposure angles did not appear to cause significant effects in this experiment since exposure angle did not show a significant effect on the results.

The significant differences in naturally occurring time of wetness due to different exposure angles did not appear to cause significant effects in this experiment since the exposure angle did not appear to have a significant effect on the results.

One-factor-at-a-time (OFAT) experiments may not have characterized the interaction between the moisture spray factor and the exposure location factor.

Application of moisture sprays in artificial weathering methods may have dramatic effects on the results and conclusions. "Incorrect" stimulation of the moisture factor in artificial weathering may impact results and conclusions from the tests. Simulating the interaction of the moisture factor and location factors observed in this study may prove especially difficult to simulate under highly artificial laboratory weathering test methods.

ACKNOWLEDGMENT

The author would like to thank the technicians at Atlas Weathering Services Group's DSET and EvTL facilities for the exposure testing and gloss measurements.

REFERENCES


